A Study to Measure and Evaluate the Effect that Vegetation has on the Emanation Rate of Radon from a Uranium Tailings Pile

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ABSTRACT

This report presents the methodology, results, and conclusions of a study conducted by DSMA ATCON LTD. on behalf of Energy, Mines, and Resources Canada as part of the National Uranium Tailings Program under DSS Contract No. OSQ83-00273, DSS File No. 14SQ.23241-3-1659.

The radon emanation rates from vegetated and unvegetated areas of the Nordic Tailings Site located near Elliot Lake, Ontario, were measured over the growing season using an aerodynamic method. By determining the change in radon concentration in ambient air passing over side-by-side vegetated and unvegetated tailing areas, estimates of radon emanation were obtained and compared without affecting the tailing surface or vegetation.

Test results showed that there was no significant difference between the radon emanation rates from vegetated and unvegetated uranium tailings. There were no obvious correlations between radon emanation rates and the observed meteorological conditions or tailings physical characteristics.

Measuring radon emanation rates by accumulator methods proved to be inappropriate due to the high variability of the measurements from place to place. A small part of this was caused by inhomogeneity of the tailings surface and the small area tested with accumulators.

EXECUTIVE SUMMARY

This report presents the results and conclusions of a program conducted by DSMA ATCON LTD. on behalf of Energy, Mines and Resources Canada as part of the National Uranium Tailings Program under Contract No. OSQ83-00273, DSS File No. 14SQ.23241-3-1659.

The objective of this project was to measure and evaluate the effect of vegetation on the emanation rate of radon from a uranium tailings pile. The information obtained in this and other studies will assist the National Uranium Tailings Program in establishing reasonable criteria for the protection of the environment and assist in the development of practical guidelines for Uranium Tailings Management.

The Rio Algom Ltd. Nordic Tailings Impoundment near Elliot Lake, Ontario, was studied over the growing season from June to September, 1984. The radon emanation from both vegetated and unvegetated tailings was estimated using the aerodynamic method developed at Guelph University, Ontario. This method estimates the average radon emanation from the increase of radon concentration in ambient air passing over test sites, considering the weather conditions and utilizing a numerical trajectory analysis procedure. This automatically averages over large areas and does not interfere in any way with either the site surface or the vegetation. The method was originally developed for use in soil science and was known to be accurate in conditions where atmospheric parameters could be estimated accurately.

It was found that the increases in ambient radon concentration across adjacent vegetated and unvegetated tailings areas 40 m wide could be measured under a variety of wind and weather conditions to the required accuracy. The increases were similar, showing that there was no significant difference between the radon emanation rates from vegetated or unvegetated uranium tailings. Portable instrumentation was employed to obtain data with sufficient accuracy to provide consistent estimates of efflux rates.

The mean value of emanation from the tailings area as a whole, as estimated by aerodynamic measurements taken at the centre of the tailings site, compared well with the mean of the side-by-side results. However, the correlation between the side-by-side results and centre results taken on the same day is insignificant, indicating that the factors affecting emanation from small upwind areas do not apply to the tailings area as a whole.

The radon concentration gradients measured in the tailings by Track Etch detectors placed beneath vegetated and unvegetated areas were not significantly different. The gradients were very steep, indicating that a large fraction of the radon produced in the upper few centimeters of the tailings escaped to the atmosphere, regardless of whether the surface was vegetated or not.

Accumulator measurements indicated that the radon emanation rate from unvegetated areas was higher than that from vegetated areas. The difference is attributed to the difficulty of sealing the accumulators to the soil through the matted vegetation cover. Leakage through this gap would lower the apparent efflux rate from vegetated areas.

The emanation rate measured with accumulators was found to be highly variable, with poor correlation between even adjacent measurements. Part of this variability results from the observed inhomogeneity of the tailings in texture and activity, but the large differences observed suggest that the short-term emanation rate from small areas is not a diffusion-limited process, and hence accumulators are not an appropriate measurement tool.

Although the mean emanation rate derived from all accumulator measurements is comparable to that derived from the aerodynamic measurements, there is no significant correlation between the measurements made on any given day by the two methods.

Correlations between the observed meteorological and soil moisture conditions and the radon efflux rate measured by either method were looked for, but none were found.

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We are thankful to the personnel at the CANMET Elliot Lake Laboratory for their assistance and allowing us the use of lab space and a number of pieces of necessary equipment.

We would also like to thank Rio Algom Ltd. for their co-operation in allowing us to remove the vegetation from an area of the Nordic Tailings Site and access to the site at all times during the study period.

We are appreciative, as well, of the Ontario Ministry of Labour, Special Services Branch, in Elliot Lake for the use of their Eberline SAC-R5 photomultiplier which replaced one of our units which had broken in transit. We would also like to thank Senes Consulting Services for providing the rain gauge data for this study.

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1. INTRODUCTION

This report presents the methodology, results and conclusions of a study conducted by DSMA ATCON LTD. on behalf of Energy, Mines and Resources Canada as part of the National Uranium Tailings Program under DSS File No. 14SQ.23241-3-1659, Contract No. OSQ83-00273.

The objective of this study was to measure and evaluate the effect that vegetation has on the emanation rate of radon from a uranium tailings pile. The information obtained in this and other studies will assist the National Uranium Tailings Program in establishing reasonable criterion for the protection of the environment and proposing practical guidelines for Uranium Tailings Management.

The Rio Algom Ltd. Nordic Tailings Impoundment near Elliot Lake, Ontario, was studied over the growing season from June to September, 1984. The radon emanation from both vegetated and unvegetated tailings was estimated using the aerodynamic model developed by Wilson, et al, at Guelph University, Ontario. By determining the change in radon concentration in ambient air passing over test sites, this aerodynamic method automatically averaged over large areas and did not interfere in any way with either the site surface or the vegetation. This method had been developed originally for use in soil science and was known to be accurate in those conditions where atmospheric parameters could be estimated accurately. This study found that the increase in ambient radon concentration can be measured to the required accuracy and portable instrumentation can obtain metrological data with sufficient accuracy to provide consistent results.

For comparison, emanation rates were also measured on both vegetated and unvegetated areas by accumulators. Although this method has been used extensively in arid areas of the American South West, the variability of results was found to be so high that the method is probably not useful in Canadian conditions.

2. SITE DESCRIPTION

2.1 Sample Locations

The Rio Algom Ltd. Nordic Tailings site, located approximately 4 km east of the town of Elliot Lake, Ontario, was chosen for this study (Figure 1). During the period of 1960 to 1968, uranium mill tailings from the Nordic mine were deposited and the surface water was drained in 1970. A grass cover was established on the site through the period 1971-1978.

It was believed during the planning phase of this project that the wind direction at the Nordic site would be predominantly from the South East, and secondly from the South West, as indicated by wind data for this site taken in 1977. Side-by-side unvegetated and vegetated areas on which simultaneous aerodynamic radon emanation tests could be conducted were chosen parallel to these directions.

During the study period, the wind often blew in a northerly direction from over the hills and down onto the tailing site. After discussions with Dr. G. Thurtell of Guelph University, an additional site at the centre of the tailings areas was chosen. As indicated on the site map, Figure 1, samples were taken at location C, the meteorological tower near the centre of the tailings site and at the upwind edge of the tailings. When the wind blew in a northerly direction over the hills, background radon samples were taken away from the tailings site. It was felt that these tests would give estimates of the overall radon emanation from the site, which was mostly vegetated. Immediately following these tests accumulator tests were made on an unvegetated patch upwind from where the aerodynamic samples were taken. It was hoped that comparing the radon emanation rates estimated by the two methods would give a comparison of vegetated tailings against unvegetated tailings.

In order to undertake aerodynamic emanation tests on side-by-side vegetation and unvegetated areas as planned, two areas were prepared; one in the South West corner, the other in the South East corner (see Figure 1). A portion of the area in the South West was already unvegetated and, as a result, was well suited for our uses.

In the south west sampling area (see Figure 2), sample locations number 1 and 2 were situated on adjacent vegetated and unvegetated patches approximately 40 meters from the tailings edge, location number 3. Radon gas samples were taken simultaneously at locations 1, 2 and 3 when the wind blew in a southwesterly direction. In this way the radon emanation from the unvegetated and vegetated patches could be compared under identical conditions. An area of approximately 40 m x 40 m in the South East corner had to be prepared by removing the vegetation and surface soil from it using a front end loader. The removed material was placed along the North to South edge, forming a wind row. In this sampling area (see Figure 3), sample locations number 4 and 5 were placed on the north end of adjacent vegetated and unvegetated patches, approximately 60 meters from the south edge of the tailings dam, location 6. In the same corner, sample locations 7 and 8 were

situated on the west edge of adjacent vegetated and unvegetated patches approximately 40 meters from the east edge of the tailings dam, location 9. As a result, radon samples could be taken in this area when the wind blew either in a southerly (locations 4, 5 and 6) or in an easterly (locations 7, 8 and 9) direction.

3. METHODOLOGY

3.1 Radon Sampling and Analysis by Scintillation Techniques

Radon gas samples were obtained and analyzed as part of a variety of methodologies, described in the following sections, aimed at characterizing the emanation of radon from the uranium tailings site. Radon gas was sampled using Eberline scintillation cells by drawing a volume of air at least three times the volume of the cell through the sample cell via a glass fiber filter. After a 3 to 8 hour wait to allow the radon daughters to come to equilibrium within the closed cell, the cell was placed within an Eberline SAC-R5 photomultiplier and counted. The size of sample cell and count time were dependent on the type of sample taken. Accumulator radon samples (Section 3.3) and radon emanation power samples (Section 3.6) were taken using 0.1 L or 0.5 L cells and counted for 10 minutes. Aerodynamic radon samples (Section 3.2) were taken using 1.4 L cells and counted for 50 minutes. Prior to using a cell for sampling, a background count for the same duration as the sample count was conducted.

The radon concentration of the air at sample time was calculated as follows:

$$Rn = \frac{c - b}{t \times f \times d} \qquad (1)$$

where:

Rn = radon concentration, mBq/m^3
c = sample count from cell
b = background count from cell
t = count time, min
f = cell efficiency factor, $cpm/mBq/m^3$
d = delay factor

The efficiency factors, f, ($cpm/mBq/m^3$) of three sample cells were derived from calibration data obtained at EML in New York. Using these calibrated cells, an intercomparison with the remaining sample cells was conducted using our Eberline equipment to determine their efficiency factors.

The delay factor, d, takes into account that the radon gas has decayed away since being sampled and is calculated as follows:

$$d = \exp(-T/7950) \qquad (2)$$

where T = time between sample and count, min.

In the case of aerodynamic emanation tests, the mid-point of the 10

minute bag sample was used as the sample time.

An error estimate of the radon concentration was calculated using standard deviations as follows:

$$\sigma_{Rn} = Rn \sqrt{\left(\frac{\sigma_n}{n}\right)^2 + \left(\frac{\sigma_F}{F}\right)^2} \qquad (3)$$

where:

σ_{Rn} = standard deviation of radon concentration, mBq/m³

n = net count rate, cpm = (c-b)/t

σ_F = standard deviation of cell efficiency factor, cpm/mBq/m³

$$\sigma_n = \sqrt{\frac{c}{t^2} + \frac{b}{t^2}} \qquad (4)$$

After counting was completed, each cell was flushed with filtered, aged, compressed nitrogen to remove the radon gas and return the cell to background level. The background counts were taken after at least a 4 hour wait.

3.2 Radon Emanation by the Aerodynamic Method

This method required sampling of ambient radon at the upwind edge of the tailings site and at a location at least 30 meters downwind on the tailings. The difference in radon concentrations gave an estimate of the radon flux from the tailings between the two sample locations.

After determining the wind direction, radon gas sampling trains were set up at the appropriate locations as described in Section 2.1. To take a sample, ambient air was pumped through a filter into a 10 litre aluminized gas sampling bag using a low flow battery operated pump for a period of 10 to 15 minutes. During this sampling period measurements were made of the wind direction and speed, temperature, and humidity. The solar intensity and barometric pressure during sampling were estimated by interpolating periodic readings taken during the day. The methodologies for these measurements are described below.

The air in each sampling bag was then transferred to a 1.4 litre scintillation cell by flushing most of the 10 litre sample through the cell and

analyzed as described in Section 3.1.

The radon emanation is estimated using an equation of the form:

$$E = \frac{1}{d} \int_{z}^{\infty} \left[\overline{u}(\overline{Rn} - \overline{Rn}_b) \right] \qquad (5)$$

where:

E	=	emanation rate (mBq/m²/s)
d	=	distance from upwind edge of source to collector
u	=	mean wind speed
$\overline{Rn}$	=	mean radon concentation at collector
$\overline{Rn}_b$	=	mean radon concentration upwind of source
z	=	roughness length of source

For a given geometry and weather condition, the equation is evaluated numerically using a trajectory simulation model developed at Guelph University (Wilson et al., I, II, III, 1981). The model uses Langrangian diffusion concepts to calculate the diffusion paths of a very large number of particles or molecules (typically the trajectories of the order of 10^4 particles are calculated). In this way the relationship between source strength and the concentration at any distance downwind from the source and at any height above the earth's surface can be determined. This relationship can be used to calculate either the source strength, if the concentration has been measured, or the concentration, if the source strength is known. The method is applicable to problems involving point, line, or area sources; area sources can be of any size.

A suitable description of the air turbulence at the time of the experiment is required for accurate trajectory calculations. The necessary information includes the Lagrangian length scales, Lagrangian velocity scales, and Lagrangian time scales as functions of position and time, in addition to averaged wind speed profiles.

The Lagrangian velocities are the vector components of the observed velocities that individual parcels of air would have if their motions could be followed as they travel across the experimental site. Thus, the time integrals of the Lagrangian velocities of a parcel give its final location, in three dimensions, relative to its location when the integration was started. The statistics of these velocities depend on the path taken by the specific parcel being followed. The Lagrangian velocity scales depend on the height of the parcel above the soil surface, the mean wind speed, the surface roughness, the stability of the atmosphere, and features of the local terrain. The velocities change very rapidly with time when a parcel is near the surface but they persist for increasingly long periods as the parcel rises. The length of time that a Lagrangian velocity persists is described statistically by its

Lagrangian time scale. This also is a function of atmospheric stability and height above the surface. The Lagrangian length scales are the products of the Lagrangian velocity and time scales. The trajectory simulation model uses these statistical descriptions of the turbulence existing above the site to calculate the rate of diffusion.

All of this information is rarely available explicitly and is estimated from more conventional weather measurements - wind speed, insolation, etc., by the first part of the program. In general, the extent and quality of the available data influence the accuracy of the calculations as would be expected. We believe that the errors introduced by the use of this method should be less than 10% of the true value, and this has proven to be correct when adequate methods of verification have been available (e.g. Wilson et al., 1983).

For the analysis of the present experiment, the required information was calculated for each run from the data that had been measured at the site during the sampling period. The trajectories of radon molecules were then calculated, for each run, using a modelled area source which had a size equal to the measured size of the experimental site. The calculations were continued from the point of radon release until the location of the concentration sampling was reached. In addition, the probability of radon from the "background" being sampled at the sampling site was calculated. The measured concentrations were then corrected to remove the effects of "background" radon.

3.3 Radon Emanation by Accumulator Method

Two pairs of accumulators were used to estimate the radon flux from vegetated and unvegetated tailings on the Nordic Tailings site.

The first pair of accumulators, referred to as small accumulators 1 and 2, were constructed of 20 cm I.D. PVC plastic pipe (Figure 4). One end of each 25 cm long pipe was bevelled to ease insertion of the accumulators into the tailings. A rubber O-ring was fitted into the edge of the opposite end of each pipe to provide a seal with the accumulator top, also made of plastic. Lines drawn on the outside of the pipes marked the height above the bevelled edge in 1 cm intervals. Two hose barbs were inserted into the side of each pipe, one half way up and the other three-quarters the way up the side. Stainless steel capillary tubes were inserted through the hose barbs and attached with rubber hose to ensure sampling from a constant location within the accumulator and equalization of interior and exterior pressures. These accumulators were based on a design used for tailings flux measurements in the American mid-west.

To make a radon emanation measurement with the small accumulator the bevelled edge was set 1-2 cm into the tailings. The accumulator top was removed for approximately 10 minutes to allow the disturbed surface and the air within the accumulator to return to equilibrium with the ambient air. Immediately upon closing the accumulator, a radon sample was taken (i.e. at t=0) as shown in Figure 3.3a. A second (and sometimes a third) radon sample was taken at 5 minutes (and 10 minutes). The small volume of the accumulator

and the high radon flux from the tailings resulted in the equilibrium concentration being reached in a very short time, necessitating such short sample intervals.

The radon data was then plotted against time and the best-fitting line or curve was calculated. The initial slope of the curve or slope of the line was calculated giving an approximation of the radon flux at time t=0. The equation for calculating the efflux rate is as follows:

$$E = \frac{dRn}{dt} \times \frac{V}{A} \qquad (6)$$

where:

E	=	radon emanation rate in mBq/m²/s
Rn	=	radon concentration, mBq/m³
t	=	time, s
V	=	volume of air in system, m³
A	=	cross-sectional area of accumulator, m²

Since $V = A \times h + V_c$, where h is the height the accumulator top surface is above the soil in meters and V_c is the volume of the sample cell in m², then the equation is as follows:

$$E = \frac{dRn}{dt}\left(h + \frac{V_c}{A}\right) \qquad (7)$$

An error estimate for the radon flux was derived to give the following:

$$\sigma_E = E\sqrt{\left(\frac{\sigma_{dRn}}{dRn}\right)^2 + \left(\frac{\sigma_h}{h}\right)^2} \qquad (8)$$

where:

$$\sigma_{dRn} = \tfrac{1}{2}\sqrt{\sigma_{Rn1}^{\ 2} + \sigma_{Rn2}^{\ 2}} \qquad (9)$$

$$\sigma_h = 1.0 \times 10^{-3}\ m$$

The second pair of accumulators, referred to as large accumulators 3 and 4, were constructed from galvanized 35 litre cans (Figure 5). Two holes were put into the bottom of each can and a 7 cm length of 0.6 cm O.D. copper tubing was fitted into each hole. A 40 cm length of tygon tubing was attached to one of the copper tubes inside each can so that when the cans were inverted the tygon tubing would hang down to approximately half the height of the can. These holes permitted sampling of the can's interior and equalization of interior and exterior pressures.

To start a radon emanation measurement with the large accumulator, the open end of the can was pressed into the surface to be tested. Over vegetated tailings it was difficult to press the can's edge into the soil below the matted vegetation. Radon samples were taken approximately five and ten minutes after setting the accumulator. The large can volume gave a slower increase in radon concentration, resulting in lower errors in rate of concentration mesurements.

The radon data was plotted against time and analyzed as for the smaller accumulator. In this case, however, the efflux was calculated as follows:

$$E = \frac{dRn}{dt} \times F \qquad (10)$$

where F is the accumulator factor equal to the ratio of accumulator volume to the area of tailings covered by the accumulator. An error estimate for radon flux was derived as follows:

$$\sigma_E = E\sqrt{\left(\frac{\sigma_{dRn}}{dRn}\right)^2 + \left(\frac{\sigma_F}{F}\right)^2} \qquad (11)$$

where:

$$\sigma_F = \frac{V}{A}\sqrt{\left(\frac{\sigma_V}{V}\right)^2 + \left(\frac{\sigma_A}{A}\right)^2} \qquad (12)$$

where V is the volume and A is the cross-sectional area of the open end of the accumulator.

3.4 Subsurface Radon Concentration Gradient

Passive track etch radon detectors, Type M, manufactured and later analyzed by Terradex Corporation were installed at depths of 10 cm and 40 cm below the surface for a period of 4 or 5 days. The open end of each detector cup was covered with a thoron filter. The cups were inserted filtered end down against undisturbed tailings and buried by backfilling over top of a polyethylene barrier.

Eight detector cups were installed on two separate occasions under vegetated and unvegetated areas. During this sample period tensiometric (Section 3.7) measurements were taken next to the detector locations and meteorological data accumulated.

The radon concentration gradient at each site was calculated from the data returned from Terradex.

3.5 Tailing Moisture Content

Samples of tailings were taken in both unvegetated and vegetated areas and at different depths at a number of locations on the tailings site. Samples were taken by pushing a 4 cm diameter corer approximately 5 cm into the tailings at a given depth and ejecting the core into a plastic bag. Five or six tailing cores taken this way, all at the same depth and within a diameter of 15 cm, constituted one sample. The plastic bag was sealed with a twist tie and labelled.

Approximately 100 g of the sample was put into a plate and its mass measured. After drying the sample in a drying oven for at least 24 hours, the sample was reweighed. The moisture content of the sample was calculated as follows:

$$\%M = \frac{m_w - m_d}{m_d} \times 100 \qquad (13)$$

where m_w and m_d equal the mass of the sample when wet and dry respectively.

3.6 Emanation Power of Tailings Samples

Tailing samples were taken and dried as described in Section 3.5. Each sample was then sealed into a canister equipped with two sampling ports (see Figure 3.6) which were easily sealed shut with hose clamps. After a three to five week period, to allow the radon gas to reach equilibrium concentration, the radon gas in the canister was sampled by connecting a sample train as illustrated in Figure 3.6 and circulating the air from the canister through the scintillation cell. The radon gas sample was analyzed as described in Section 3.1.

The radon concentration in the container, Rn, is converted to the emanating power, P, as follows:

$$P = \frac{Rn \times V}{k \times m_d} \qquad (14)$$

where:

P = emanating power, mBq/g
Rn = radon concentration in the Lucas cell, mBq/m³
V = container volume minus tailings sample volume plus sample train volume, m³
M_d = mass of the dried sample, g

k = 1 - exp(-t/132.5) = percentage of equilibrium concentration where t = length of time sample was sealed in container in hours

An error estimate for the emanating power is calculated as follows:

$$\sigma_E = \sqrt{(\frac{\sigma_{Rn}}{Rn})^2 + (\frac{\sigma_V}{V})^2 + (\frac{\sigma_m}{m})^2} \qquad (15)$$

where σ_{Rn}, σ_V and σ_m are the standard deviations of Rn, V and m (identified above) respectively.

To study the effect of moisture content on emanation power five samples, selected to represent different tailings areas and different original moisture contents, were tested for radon emanation under a range of moisture contents. A predetermined amount of water was added and completely blended into the sample which had been dried and weighed. The sample was weighed before resealing it into the container. After a three to five week period the container was sampled and analyzed as before. Immediately after radon sampling, the sample was removed from the can and reweighed to determine its actual moisture content since some condensation had occurred. Each of the five samples was tested this way under about five or six different moisture contents, ranging from 0 to 30 percent moisture by weight.

3.7 Tailings Tensiometric Measurements

Tensiometric, or soil pressure, measurements were made on the tailings site using a portable "Quick Draw" Soil Moisture Probe, Model 2900F. After coring a hole into the tailings with the tapered coring tool supplied, the porous ceramic tip of the probe was inserted. The pressure gauge on the

probe registered the suction force by which water was withdrawn through the ceramic tip into the tailings. The design of the probe allowed for quick analysis of the tailing pressure. Measurements were taken at various locations at depths of 0, 10, 20, 30, and 40 cm. Measurements at "0 m" were just below the surface. Readings were given in kilopascals.

Tailing tension is created by the attraction that each tailing particle has for the water in the tailings. Water forms a thin film around each particle and collects in the capillary spaces between them. As the tailings become drier, these films become thinner and the attraction increases. This tension draws water from the tensiometer through pores in the ceramic tip. Water is drawn from the tensiometer by the tailings until the vacuum created inside the tensiometer is just sufficient to overcome the suction of the tailings. At this equilibrium the vacuum inside the probe is equal to the tailing tension at the probe tip.

3.8 Tailings Particle Size Distribution

The particle size of any fraction of a soil (or tailings) sample is defined here as the width of the smallest square opening through which the particle can pass. The particle size distribution of a tailing sample gives the proportions of the various sizes of particles which the sample contains. The proportions are represented by the relative weights of each stated size class.

Tailing samples were taken as described in Section 3.5. A representative portion of each sample was weighed, dried overnight at 105°C, and reweighed to determine their water content. The samples were treated with hydrogen peroxide followed by filtration and washing to remove organic matter. After redrying and reweighing the samples, a solution of calgon in water was added and the suspension agitated overnight to ensure complete dispersion of particles.

Each suspension was transferred to a set of sieves and these placed on a sieve shaker. For this analysis sieve numbers 10, 18, 35, 60, 100, 140 and 270 were used. After drying each sieve and its contents, they were weighed. The percentage of the total sample weight of each fraction was plotted against particle diameter, as defined by the sieve size, to give the particle size distribution curve for each sample.

3.9 Tailing Bulk Density

The bulk density (D_b) of a soil is the ratio of the mass to the bulk volume of soil particles plus pore spaces in a sample. The bulk density is used in converting water percentage by weight to content by volume and in calculating porosity when the particle density is known.

Using the core method as described by G.R. Blake (1965), two samples were taken from each of the two depths, 5 cm and 30 cm, from three vegetated and three unvegetated areas of the tailings site. Cores were taken by pressing a 5 cm long metal pipe carefully into the undisturbed section of tailings of interest. The filled cores were then carefully dug out, leaving 1-2

cm of tailings on both ends, and packed with tailings into a plastic bag for transport to the lab. At the lab the tailings sample was removed from its packing and the excess material trimmed from both ends of the core. The sample volume in the core was the same as the volume of the sample holder. The sample was then transferred to a container, placed in an oven at 105°C until constant mass was reached, and its mass was measured. The bulk density was calculated as the oven-dry mass of the sample divided by its volume and expressed in units of kg/m^3.

3.10 Tailing Saturated Hydraulic Conductivity

The saturated hydraulic conductivity (K_s) is a measure of the medium's ability to transmit water when saturated. Using one 5 cm long core sample from each site and depth as described in Section 3.9, the tailing saturated hydraulic conductivity was measured. Supported in the corer, the sample was saturated with water. Then, using the falling-head method described by A. Klute (1965), the sample was sandwiched between porous plates and placed in a tank under a column of water (standpipe) of a smaller diameter than that of the sample. The time, t, it takes for the water in the column to fall from height, H_1, to height, H_2, above the surface of water contained in the tank was measured. The saturated hydraulic conductivity (K_s) was calculated as follows:

$$K_s = \frac{(A_1 \times L)}{(A_s \times t)} \ln \frac{(H_1)}{(H_2)} \qquad (16)$$

where A_1 is the cross-sectional area of the column of water, L is the length of the sample, and A_2 is the cross-sectional area of the sample. K_s was expressed in units of m/s.

3.11 Tailing Desorption Characteristics

The terms desorption and sorption, as applied to soil, usually refer to the processes of release and uptake of water. Desorption usually refers to a monotonically decreasing water-content change, while sorption refers to the reverse process. Desorption and sorption data usually consist of equilibrium or steady-state values of water content of soil as related to some controlled physical property such as vapor pressure or matric suction.

Tailing sample cores of 2.5 cm long were taken as described in Section 3.9 and the pressure plate procedure as described by Richards (1965) was employed to develop their desorption characteristic curves. The 2.5 cm cores were unpacked from the plastic bags in which they were transported and excess tailings were trimmed off both ends. After being saturated the core was weighed, placed on a pressure plate, and enclosed in a pressure vessel. The samples were subjected to matric potentials of - 5, -10, -33, and - 1500 kPa. After at least 24 hours at each matric potential, the samples were assumed to have reached an equilibrium weight and they were again weighed. After weighing at the lowest potential the samples were oven dried at 105°C for 24 hours and reweighed.

The volumetric water content, W (m water)³/(m bulk)³ of the tailings at different matric potentials was calculated as follows:

$$W = \frac{V_w}{V_b} = \frac{M_w}{d_w V_b} \qquad (17)$$

where

M_w = mass of water, kg
d_w = density of water, kg/m³ water
V_b = bulk volume, m³ bulk

The available water content, W_A, was calculated as the difference between water content at a suction of -10 kPa and -1500 kPa. Plotting water content against pF = $-\log_{10}$ (-matric pressure in cm water head) gives the sample's desorption characteristic curve.

3.12 Meteorological Data

Measurements of temperature, humidity, barometric pressure, solar intensity, and wind speed and direction were taken to characterize the micro-meteorological conditions existing at the time of aerodynamic radon flux tests.

Dry and wet bulb temperature measurements were taken at the 1 meter height using a sling psychrometer. Relative humidity levels were obtained using the psychrometer slide rule supplied with the sling.

Barometric pressures were read from an aneroid barometer in inches of mercury periodically through the day during testing periods from July to September. For the May and June test periods, hourly altimeter correction readings from the local airport were obtained and converted to local pressure. Readings were converted to kPa.

Solar intensity in W/m² and integrated solar energy in kWh/m² were obtained using a silicon cell pyranometer, Haenni Model 118. The sensor was installed horizontally, away from any interferring shadows, at approximately 3 metres above the ground near the tailings site. Solar intensity readings were taken periodically throughout each test day. Solar energies were continually monitored and integrated from June to September 1985.

Daily rain gauge data for all test periods were obtained from Senes Consulting Ltd. who had a complete meteorological package installed in the town of Elliot Lake, approximately 4 kilometers from the tailings site. The amount of daily precipitation was measured using a tipping bucket rain gauge and recorded in inches, which were converted to mm.

During the test periods in May and June, the average wind speed during

aerodynamic radon emanation tests was estimated from air flow measurements taken with a rotating fan anemometer. The instrument was directed into the wind at a height of 1 m and readings in ft/min were taken at intervals during the test period. The readings were averaged and converted to km/h. The resulting estimates had an error of approximately 2 km/h.

During the test periods in July to September, the average wind speed during aerodynamic radon emanation tests was measured using a run-of-wind cup anemometer supported on a tripod at a height of 1.0 metre above the ground. The counter on the side of the anemometer recorded kilometers of wind run as converted from the number of cup rotations. Average wind speed was calculated from the difference between successive counter readings divided by the time interval between readings. The operating range of the model used was 1.8 km/h to 126 km/h with an accuracy of 0.4 km/h over the observed range of 2 to 8 km/h.

During the May and June test periods, the average wind direction during aerodynamic radon emanation tests was estimated by taking compass readings of the wind direction periodically during the test period. The readings were averaged and converted to degrees clockwise from North. The resulting estimate has a standard deviation of approximately 45°.

During the July to September test periods, the average wind direction during aerodynamic radon emanation tests was measured using a wind vane supported on a tripod at a height of 1.0 metre above the ground. The vane was equipped with a rheostat whose resistance varied from 0 to 50 ohms when the vane was rotated from 0 to 360 degrees. The tripod supporting the vane was positioned so that the resistance, as read using a digital multimeter, was 25 ohms when the vane pointed South according to a compass. During the radon sample the multimeter was read at 15 second intervals. The readings were averaged over the sample period and converted to degrees clockwise from North. The standard deviation was calculated.

3.13 Test Site Gamma Survey

The relative near surface gamma activity at the experimental sites was estimated by a walk-over survey carried out with an EDA GRS400 portable scintillometer.

3.14 Vegetation Gamma Spectroscopy

Plants may transfer radon from the soil to the air by taking in soil water containing radon and evaporating that water and its contained radon from their leaves. Water enters a plant by diffusion through the membrane barrier of the root surface. Radon diffuses much more slowly than the water molecule, so that radon concentration in the plant water should be only a fraction of the radon concentration in soil water.

A check on the radon content of plants was carried out in September when the highest emanation values were obtained. The temperature was 7°C, humidity 82%, and solar intensity 355 W/m². Approximately 300 g of Birdsfoot

Trefoil was packed into a 1 litre polyethylene container, which was sealed and counted on a shielded 7.5x7.5 cm NaI detector 3 times over a 43 hour period.

4. RESULTS AND DISCUSSION

4.1 General

The final results of all radon emanation data are tabulated in Table 1 by date, location and time. The calculated absolute or percentage error for each radon emanation result is given in brackets after each entry. Page 7 of Table 1 explains the sample location symbols and Figure 1 locates the accumulator and aerodynamic test sites on a map of the Nordic Tailings Site. Aerodynamic sample locations are indicated in Figures 2 and 3 as explained in Section 2.1.

The meteorological conditions observed during the tests are also indicated on Table 1. The absolute errors in wind speed and direction are given in brackets after each entry. The rain gauge was read once a day in the afternoon but is usually placed on the top line of each day's data. Occasionally surveyors would make comments on the weather and these are included in the Rain column.

4.2 Radon Emanation by Aerodynamic Method

The results from aerodynamic estimates of radon emanation, both the side-by-side vegetated and unvegetated tests and centre measurements, were analyzed by Dr. G. Thurtell at Guelph University. These results are tabulated in Table 1 and are plotted against time in Figures 7 and 8.

4.2.1 Side-by-Side Measurements

The side-by-side aerodynamic emanation test results showed detectable and similar increases in radon concentration over similar distances which indicates that the radon emanation from vegetated and unvegetated areas are similar. This result is true, regardless of any data deficiencies that may influence the estimated value of radon emanation rates.

The emanation rates from vegetated areas were plotted against those from unvegetated areas taken at the same time and the resulting graph is shown in Figure 9. The average ratio of the emanation rates from vegetated and unvegetated sites was 1.06 with standard deviation 0.16, which is not statistically different from unity. The correlation coefficient between the pairs of measurements was 0.94, indicating that the emanation rates from each type of area were affected almost equally by changes in weather conditions.

The means and standard deviations of all paired emanation rate measurements on vegetated and unvegetated areas were 4140 (1450) mBq/m²/s and 3710 (1150) mBq/m²/s respectively. These are not statistically different.

The conclusion from these measurements is that the radon emanation rate from vegetated and unvegetated areas is the same, and that the effect of vegetation on the emanation rate is without practical significance.

These measurements do not exclude a slight reduction by vegetation, for

there were indications that the near surface radium content (Section 4.10) is higher on vegetated areas than for the unvegetated areas. All other things being equal, the radon emanation from the vegetated areas might be higher than from the unvegetated areas.

Figures 7 and 8 show that the emanation levels, as estimated using the aerodynamic method, varied quite considerably from June to September. Correlations with the observed meteorological and soil moisture conditions were looked for, but none were found.

4.2.2 Centre Measurements

The results of measurements taken at the centre of the tailings site are quite variable, with emanation rates ranging from 2110 to 6590 mBq/m²/s. The mean was 3910 mBq/m²/s with a standard deviation of 1120 mBq/m²/s. This compares well with the mean of 3930 mBq/m²/s given by all the side-by-side measurements. However, the correlation between the centre measurements and side-by-side measurements made on the same day was insignificant, indicating that the factors affecting emanation from small areas need not apply to the tailings area as a whole.

These results did not correlate to accumulator results from vegetated areas taken on the same day. In consequence, centre aerodynamic results can not be compared with accumulator results from unvegetated areas with any degree of confidence.

4.3 Radon Emanation by Accumulator Method

The results from the accumulator tests on vegetated and unvegetated areas using both small and large accumulators, were plotted against time (Figure 10). The results showed considerable variability, ranging from 110 to 11,200 mBq/m²/s, both in side-by-side measurements using large and small accumulators and in measurements taken from day to day. The overall mean of the accumulator data is 3650 mBq/m²/s.

Figure 11 shows that the radon emanation from the unvegetated areas was higher than from the vegetated areas. The mean radon emanation from 48 tests on unvegetated areas is 4490 mBq/m²/s with a deviation of 3060 mBq/m²/s whereas the radon emanation from 18 tests on vegetated areas is 1440 mBq/m²/s with a deviation of 970 mBq/m²/s.

This difference is thought to be a result of the measurement methods. In general, the small accumulators were used to measure the emanation from unvegetated areas whereas the large accumulators were used to test vegetated areas. As it was more difficult to seal between the large accumulator and the matted vegetation cover than it was to seal between the small accumulator and unvegetated tailings, the measurements on vegetation are biased low by leakage.

Figure 10 shows that the emanation levels varied quite considerably from June to July which might suggest an effect due to differing conditions.

Based on the observed meteorological and soil moisture conditions, however, there are no obvious correlations between emanation levels and conditions.

The variation in emanation rates as estimated by the accumulator methods (range 110 to 11,200 mBq/m²/s) is much more extreme than that estimated by both the side-by-side and centre-edge aerodynamic methods (range: 2110 to 6590 mBq/m²/s). Part of this variability is the result of inhomogeneity of the tailings site surface. The aerodynamic method averages over an area of 1000 m², whereas the accumulators measure an area of 0.3 m². Inhomogeneity of the tailings site surface has more effect on accumulator results precisely because of the different sizes of areas being tested. However, the extreme variability of even closely spaced accumulator measurements suggests that the emanation rate over small areas is not a diffusion limited process, hence accumulators are not an appropriate measurement tool.

4.4 Tailings Radon Concentration Gradient Using Terradex

The results returned by Terradex and the calculated concentration gradients are presented in Table 2.

The means and standard deviations of the radon gradients for the vegetated and unvegetated areas sampled are -6.0×10^3 (7.0×10^3) mBq/m³/m and -5.6×10^3 (2.9×10^3) mBq/m³/m. The difference between gradients under the vegetated and unvegetated areas measured is not significant. The overall mean and standard deviation are -5.8×10^3 (4.8×10^3) mBq/m³/m. That is, the radon concentration increases by 5.8×10^3 mBq/m³ per meter of depth. This steep gradient indicates that a large fraction of the radon produced in the upper few centimeters of the tailings escapes to the air regardless of whether the surface is vegetated or not.

4.5 Radon Emanation Power of Tailings Samples

The results of the emanation power tests conducted on dried tailings samples are listed in Table 3 by sample time and location. The estimate of absolute error is given in brackets following each entry.

The radon emanation power of dried tailings samples ranged from 359 mBq/g to 2540 mBq/g. The mean and standard deviation of all the samples taken from unvegetated and vegetated areas are 520 (180) mBq/g and 790 (310) mBq/g respectively. Although the mean of the vegetated area samples is slightly higher, the difference is not significant.

The results of the study into the effect of moisture content on radon emanation power are presented in graph form in Figure 12. This graph indicates a sharp increase in emanation power with only a slight increase in moisture content as compared to dried samples. The rise in emanation power levels off for all samples at approximately 3% moisture (by mass).

4.6 Tensiometric Measurements, Tailings Moisture Content

The results of in-situ tensiometric measurements and tailing moisture contents, as determined by the gravimetric method, are presented in Table 4. The date, time and location of the test or sample are given.

There is no direct correlation between tailings tensiometric readings and tailing moisture content. For the most part the tailings maintained a fairly low tension, indicating a high moisture content.

4.7 Tailings Particle Size Distribution

Particle size analysis was conducted on six tailings samples by Dr. D.E. Elrick at Guelph University. The results have been plotted together on a semi-log graph, Figure 13, which shows the percentage of particles equal to less than the indicated size against the seive numbers and particle diameter. These results indicate that all sites had greater than 90% sand with mid-particle diameters varying between 145-170 μm.

4.8 Bulk Density, Saturated Hydraulic Conductivity, and Desorption Characteristics

"Undisturbed" soil cores taken from vegetated and unvegetated areas at the Nordic Tailings Site were analyzed by Dr. D.E. Elrick at Guelph University for bulk density, saturated hydraulic conductivity and soil water characteristics values.

Two cores from each of the two depths (approx. 0.03 to 0.10 m and approx. 0.30 to 0.40 m) were obtained from three vegetated and three unvegetated sites at the Nordic Tailings Site (Table 5). One core from each depth was used for the saturated hydraulic conductivity (K_s) measurement and the other was used to determine the desorption characteristic curve (pF versus W). The bulk density (D_b) was determined on both cores.

The average bulk density values of the "undisturbed" core sample are given in Table 6. The overall average bulk density of the 24 core samples is 1.42×10^3 kg/m³. The bulk density varied from 1.32×10^3 kg/m³ in the surface layer of the vegetated site to 1.50×10^3 kg/m³ at the subsurface depth of the unvegetated site. The lower bulk densities found on the vegetated sites can be attributed to the increased organic matter contents that were obviously present in the samples. The values found at both depths on the vegetated and unvegetated sites do not appear to be high enough to restrict plant growth and lie within the anticipated range of fine sands.

The hydraulic conductivity values of the "undisturbed" soil cores are given in Table 7. Because studies of the field variability of hydraulic conductivity have shown K_s to be log normally distributed (Warrick and Nielsen, 1980), the geometric means of the individual K_s values are also given. The conductivity classes ranged from rapid (surface layer, unvegetated) to moderate at the other sites with an overall geometric mean of 1.2×10^{-5} m/s (moderate). This is not an unexpected value given the fine sandy nature of

the tailings.

The desorption data obtained from the soil cores is given in Table 8 and the soil water desorption characteristic curves are shown in Figures 14 to 17. More variability was found than anticipated and this may be attributed to the high root and fibrous material content of some cores. The available water content (the difference between the water content at a suction of -10 kPa and -1500 kPa) varied from a low of 0.09 m^3/m^3 to a high of 0.24 m^3/m^3 with an average of 0.15 m^3/m^3. Thus the tailings soils contain an adequate amount of water to support plant growth.

The moisture desorption curves show that the pore size distribution of the unvegetated tailings areas in the south east corner differs from the vegetated area. The measured in-situ soil tension in both areas ranged between 10-20 kPa or pF values of 2.0 to 2.3. This translates into saturations of 20 to 40%, compared to saturations of 50 to 80% for the vegetated area. As the ease of radon movement through the soil depends partly on the saturation, the radon emanation from this unvegetated area is potentially higher than from the vegetated area. The pore size distributions of vegetated and unvegetated areas in the south western corner are much more similar so their potential emanation rates are expected to be similar.

The pF of all the tailings samples rises rapidly if moisture is reduced below that corresponding to a pF of 2.3. This indicates that the tailing tension measured in the field is close to that corresponding to the residual saturation. Given the good hydraulic conductivity of the tailings, this explains the small variation in tension. Precipitation falling on the tailings will rapidly drain through the surface layer, so the saturation will always be close to the residual saturation value.

4.9 Meteorological Data

The conditions observed during radon emanation tests are indicated in Table 1 and discussed in Section 4.1.

4.10 Gamma Spectroscopy and Walk-over Survey Results

The relative near surface ^{214}Bi concentrations which is related to the radon and radium concentrations in the ground was estimated by a walk-over survey carried out with an EDA GRS400 portable scintillometer. The spatial variability was high (±40%) at both sites.

The relative ^{214}Bi activities (1.76 MeV gamma channel) were:

South West Corner	- vegetated	0.8
	- unvegetated	0.65
South East Corner	- vegetated	1.0
	- unvegetated	0.77

On average, the near surface ^{214}Bi and hence radon and radium

concentration is approximately 20% higher on the vegetated areas. All other things being equal, we would expect the radon release from vegetated areas to be 20% higher than from the unvegetated areas.

4.11 Vegetation Gamma Spectroscopy

The check on the radon content of plants growing on the tailings site was conducted in September. One 300g sample of Birdsfoot Trefoil was sealed into a 1 litre container.

The total count rate from the sample was initially 19.7 counts/s, fell to 15.3 counts/s in 24h and was 15.3 counts/s at 43h. The background count rate was 8.6 c/s. The net count rate in the 1.65 - 1.9 MeV channel (radon daughter ^{214}Bi) fell from 0.8 counts/s to 0.2 counts/s in 24h, and was 0.3 counts/s at 43h.

Radon 222 will decay only 16% in 24 hours, so the initial decreases are too rapid to be caused by radioactive decay of radon in equilibrium with its daughters. Most of the ^{214}Bi initially present is unsupported, suggesting that it was deposited on the plant surface by the radon escaping from the tailings to the atmosphere. The constancy of count rate from 24 to 43 hours shows that the ^{214}Bi activity due to radon in plant water cannot be much greater than ^{214}Bi produced by the radium in the plant tissues, or else a decrease in activity would have been visible. An accurate counting calibration for this geometry was not available, but the count rates indicate a total activity of a few hundred mBq/g, typical for plants growing on the tailings.

The root system is therefore an effective diffusion barrier against radon, and even at times of high transpiration, the amount of radon transported in soil water by the plants will be only a fraction of that released from the top 1 cm of tailings.

5. CONCLUSIONS

Detectable and similar radon concentration increases were measured over vegetated and unvegetated tailings areas 40 m wide under a variety of wind and weather conditions. These increases were converted to average radon efflux rates by a numerical trajectory analysis procedure.

The results of these side-by-side aerodynamic measurements showed that there was no significant difference between radon emanation rates from vegetated as compared to unvegetated uranium tailings. This result does not exclude a slight reduction in emanation rate by vegetation for there were indications that the radium content of near surface vegetated tailings was higher than that of unvegetated tailings in the areas tested. If vegetation had no effect on the emanation rates then it might have been expected that the rates from the vegetated areas would have been higher.

The mean value of emanation from the tailings area as a whole, estimated by aerodynamic measurements taken at the centre of the tailings site compared well with the mean of the side-by-side results. However, the correlation between the side-by-side results and centre results taken on the same day is insignificant, indicating that the factors affecting emanation from small upwind areas do not apply to the tailings area as a whole.

Correlations of the aerodynamic results with the observed meteorological and soil moisture conditions were looked for but none were found.

The radon concentration gradients measured in the tailings by Track etch detectors placed beneath vegetated and unvegetated areas were not significantly different. The steepness of the gradients indicate that a large fraction of the radon produced in the upper few centimeters of the tailings escaped to the atmosphere, regardless of whether the surface is vegetated or not.

Measurements with accumulators indicated that the radon emanation rate from unvegetated areas was higher than that from vegetated areas, but the difference is a consequence of measurement methods. It was difficult to seal the accumulators to the soil through the vegetation cover. Leakage through the gap would lower those results.

The emanation rate measured by both large and small accumulators was found to be highly variable. The correlation between even adjacent measurements was poor. Part of this variability results from the observed inhomogeneity of the tailings in texture and activity, but the large differences observed suggest that the short term emanation rate from small areas is not a diffusion limited process, and hence accumulators are not an appropriate measurement tool.

Although the mean emanation rate derived from all accumulator measurements compares well with that derived from the aerodynamic measurements, there is no significant correlation between the measurements

made on any given day by the two methods.

Correlations between accumulator results and meteorological and soil moisture conditions were looked for but none were found.

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TABLE 1 - RADON EMANATION AND METEOROLOGICAL DATA

DATE	* LOCATION	TIME	RADON EXHALATION ($mBq/m^2/s$) Aerodynamic	RADON EXHALATION ($mBq/m^2/s$) Avg. Acc.	TEMP. (^oC)	RH%	P (kPa)	SOLAR INTENSITY (W/m^2)	RAIN (mm / day)	WIND SPEED (km/h)	WIND DIRECTION ^oE from N.
June 21/84	C	14:37-47	4290 (20%)		23.8	38	97.96↓	600	Nil	5.1(±1)	248(±23)
	E	15:13-23			24.8	35	"	"		9 (±2)	~270
	SW-UV	15:27-14			25.2	36	"	"		~9	"
		15:50-16:10		4290 (±190)	25.2	36	"	"		"	"
	C	22:01-11	2960 (81%)		14.8	80	97.96↓	0		1.0(±1)	180(±45)
	E	22:22-32			15.6	76	"	0		"	"
June 22	C	10:39-51	4510 (23%)		21.0	42	97.89	570	Nil	9.0(±2)	113(±23)
	E	11:07-19			20.5	48	"	"		"	"
	UV-1	11:35-52			22.5	38	"	"		~10	~135
		"			"	"	"	"		"	"
		11:54-12:15		4630 (±150)	"	"	"	"		"	"
		"			"	"	"	"		"	"
	C	21:35-46	5030 (80%)		13.5	87	97.79↓	0		1.0(±1)	90(±15)
	E	21:35-22:04			13.2	83	"	0		"	"
June 23	UV-2	10:33-50			22.0	79	-	400	Nil	~5	~135
		"			"	"	-	"		"	"
		10:54-11:15		2960 (±110)	"	"		"		"	"
		"			"	"		"		"	"
	C	21:28-40	4290 (29%)		19.2	55	97.25↓	0		3.2(±1)	135(±15)
	E	21:45-57			19.8	54	"	"		4.6(±1)	"
June 24	C	10:41-52	3090 (24%)		14.8	90	95.96↑	<100	prior to sample 13	13.5(±3)	270(±15)
	E	11:07-18			14.6	85	"	"		22 (±5)	"
	UV-1	11:30-47			15.8	79	"	"		14 (±2)	270(±20)
		"			"	"	"	"		"	"
		11:49-12:10		7700 (±370)	"	"	"	"		"	"
		"			"	"	"	"		"	"

* see page 7

TABLE 1 - RADON EMANATION AND METEOROLOGICAL DATA

DATE	* LOCATION	TIME	RADON EXHALATION ($mBq/m^2/s$) AERODYNAMIC	RADON EXHALATION ($mBq/m^2/s$) Avg. Acc.	TEMP. (^oC)	RH%	P (kPa)	SOLAR INTENSITY (W/m^2)	RAIN (mm / day)	WIND SPEED (km/h)	WIND DIRECTION ^oE from N.
June 25/84	C	12:34-46	2220 (28%)		14.8	60	96.84↑	400	0.5.	7.3(±2)	293(±23)
	E	12:59-13:11			15.3	60	"	"		9.1(±2)	270
	UV-4	13:24-41			15.5	56	"	"		10 (±2)	290(±20)
		"			"	"	"	"		"	"
		13.43-14:03		11200 (520)	"	"	"	"		"	"
		"			"	"	"	"		"	"
	C	21:30-40	4330 (80%)		10.0	90	96.84↑	0		1.0(±1)	293(±20)
	E	22:00-10			12.0	77		"		2.7(±1)	270
June 26	C	08:17-28	4220 (22%)		12.6	89	96.87↑	180	Nil	4.6(±1)	160(±20)
	E	08:38-49			11.8	87	"	"		5.0(±1)	135(±20)
	UV-5	08:57-9:14			12.2	82	"	"		6.4(±1)	160(±20)
		"			"	"	"	"		"	"
		09:15-:33		6700 (190)	"	"	"	"		"	"
		"			"	"	"	"		"	"
July 17	C	15:00-15			20.3	67	96.06↑	~800	rain all morning to 14:00	8.2(±1)	225(±20)
			4000 (16%)								
	E	16:00-10			19.3	70	"	~500		18.3(±1)	250(±20)
	SW-UV	16:25-35	3440 (±670)		21.2	63	"	600-700	4.3	9.0(±1)	250(±20)
	SW-V	16:45-55	3550 (±700)		19.9	62	"	~800		8.2(±1)	270(±45)
	SW-UV	17:34-:56			18.7	62	"	400-500		8.0(±1)	270(±20)
		17:37-18:00		6330 (220)	"	"	"	"		"	"
	SW-V	18:33-55		2630 (110)	19.4	58	"	~400		6.4(±1)	"
		"			"	"	"	"		"	"
July 20	C	10:05-17	3890 (13%)		23.5	54	97.25	400-500	2.	2.7(±1)	259(±25)
	E	15:08-21			27.0	31	97.21	850		6.9(±.3)	276(±22)
	SW-UV	15:05-19	4660 (±670)		25.6	34	"	"		"	"
	SW-V	15:12-25	3810 (±560)		27.0	31	"	"		"	"
	SW-V	15:38-16:26		560 (70)	24.6	48	"	400		7.7(±.3)	286(±21)
		"			"	"	"	"		"	"
	SW-UV	16:00-38		960 (70)	"	"	"	"		"	"
		"			"	"	"	"		"	"

* see page 7

TABLE 1 - RADON EMANATION AND METEOROLOGICAL DATA

DATE	* LOCATION	TIME	RADON EXHALATION (mBq /m^2/s) AERODYNAMIC	RADON EXHALATION (mBq /m^2/s) Avg. Acc.	TEMP. (^{o}C)	RH%	P (kPa)	SOLAR INTENSITY (W/m^2)	RAIN (mm / day)	WIND SPEED (km/h)	WIND DIRECTION ^{o}E from N.
July 21/84	SW-UV	11:54-12:08	4480 (±670)		26.0	47	97.72	800	2.	5.0(±.3)	224(±30)
	E	11:57-12:12			25.8	41	"	"		"	"
	SW-V	11:59-12:14	3890 (±590)		26.1	38	"	"		"	"
July 22	E	13:48-14:02			26.3	45	97.75↓	600	2.	7.5(±.3)	189(±35)
	SE(S)-UV	13:55-14:07	2070 (±370)		25.2	47	"	"		"	"
	SE(S)-V	13:58-14:15	3260 (±480)		26.0	47	"	"		"	"
	SE(S)-V	15:56-16:27		520 (40)	25.0	52	97.58↓	300		7.5(±.3)	239(±5)
	"	"			"	"	"	"		"	"
	SE(S)-UV	16:23-17:06		2290 (40)	-	-	97.55↓	250		"	"
					-	-	"	"		"	"
July 24	C	09:32-44	3440 (12%)		17.9	51	97.65	450	Nil	11.5(±.2)	354(±14)
	E	10:43-54			20.6	45	97.69	630		3.6(±.2)	"
Aug. 13	C	14:56-15:07	6590 (10%)		27.8	43	97.72↓	700	Nil	3.1(±.2)	60(±84)
	E	15:32-43			23.0	76	"	~600		1.6(±.2)	216(±58)
Aug. 14	V-2	10:59-11:24		1520 (70)	~25	~70	-	~300	Trace	3 (±.3)	250(±70)
	"	"			"	"		"		"	"
	UV-2	11:03-:28		6770 (300)	"	"		"		"	"
	"	"			"	"		"		"	"
	C	14:38-48	3290 (10%)		24.8	72	97.48↓	~150		5.2(±.2)	310(±32)
	R	15:02-14			23.0	71	"	"		-	-

* see page 7

TABLE 1 - RADON EMANATION AND METEOROLOGICAL DATA

DATE	* LOCATION	TIME	RADON EXHALATION (mBq/m²/s) AERODYNAMIC	RADON EXHALATION (mBq/m²/s) AVG. ACC.	TEMP. (°C)	RH%	P (kPa)	SOLAR INTENSITY (W/m²)	RAIN (mm / day)	WIND SPEED (km/h)	WIND DIRECTION °E from N.
Aug. 15/84	SW-UV	10:50-11:01	3520 (±520)		21.6	84	97.21 ↑	~180	8.9	6.0(±.3)	259(±24)
	SW-V	10:51-11:03	2150 (±410)		21.4	85	"	"	rain last	"	"
	E	10:52-11:04			22.1	82	"	"	2 days	"	"
	SW-UV	15:10-:40		4030 (±110)	25.0	72	97.08 ↓	200	- surface		
		"			"	"	"	"	ponding		
	SW-V	15:13-:45		1100 (±40)	26.0	68	"	"			
		"			"	"	"	"			
	SW-V	15:45-:58	2520 (±590)		26.0	68	"	"		7.0(±.3)	250(±13)
	SW-UV	15:46-16:00	1850 (±560)		25.6	69	"	"		"	"
	E	15:48-16:04			25.6	66	"	"		"	"
Aug. 18	C	16:38-:49	4330 (10%)		-	-	96.81 ↓	~100	Nil	4.6(±.2)	41(±19)
	R	18:11-:22			17.6	84	"	"			
	UV-6	17:33-:57		3740 (±110)	-	99	"	"	drizzle		
		"			-	99	"	"	"		
Aug. 19	C	11:24-36	5370 (11%)		18.6	65	97.55 ↓	~700	Nil	5.4(±.2)	45(±34)
	R	13:12-23			19.6	49	"	"		-	-
	UV-7	12:16-:36		5740 (±150)	18.7	63	97.52 ↓	"		-	-
		"			"	"	"	"		-	-
	UV-8	13:40-14:00		10800 (±300)	20.2	47	97.48 ↓	"		-	-
		"			"	"	"	"		-	-
Aug. 20	C	10:44-55	2110 (14%)		21.1	63	97.58 ↓	230	6.1	5.5(±.2)	247(36)
	E	11:36-48			20.7	69	97.52 ↓	"		4.8(±.2)	253(31)
	SW-UV	11:35-46	2520(±410)		"	"	"	"		"	"
	SW-V	11:36-47	4440(±590)		"	"	"	"		"	"
	SW-UV	12:19-42		3110 (70)	-	-	"	~200		-	-
		"			-	-	"	"		-	-
	SW-V	13:01-21		3030 (70)	-	-	97.48	600		-	-
		"			-	-	"	"		-	-
	C	16:57-17:08	3220 (13%)		24.3	55	97.38	500		8.4(.2)	213(31)
	E	17:30-45			24.3	55	"	400		7.2(.2)	213(21)
	SW-UV	17:30-44	3180(±560)		"	"	"	"		"	"
	SW-V	17:31-45	5620(±700)		"	"	"	"		"	"

* see page 7

TABLE 1 - RADON EMANATION AND METEOROLOGICAL DATA

DATE	* LOCATION	TIME	RADON EXHALATION ($mBq/m^2/s$) AERODYNAMIC	RADON EXHALATION ($mBq/m^2/s$) AVG. ACC.	TEMP. (^oC)	RH%	P (kPa)	SOLAR INTENSITY (W/m^2)	RAIN (mm / day)	WIND SPEED (km/h)	WIND DIRECTION ^oE from N.
Aug. 22/84	C	10:49-11:00	4770 (10%)		20.2	81	96.84	580	0.5	8.4(±.2)	60(22)
	R	12:21-31			23.0	63	"	~700		-	-
	UV-9	11:42-12:09		6250 (±150)	-	-	"	~700		-	-
		"			-	-	"	"		-	-
Sept. 24	SE(N)-UV	9:52-41	-890 (±590)		10.8	63	97.58↓	50	Nil	10.3(±.3)	107(14)
	SE(N)-V	9:31-43	3110 (±780)		"	"	"	"		"	"
	E	9:46-57			"	"	"	"		"	"
	SE(N)-V	9:33-:44		1630 (±150)	"	"	"	"		"	"
		9:50-10:01			"	"	"	"		"	"
	SE-UV	10:04-:16		370 (±70)	"	"	"	"		"	"
		10:35-:55			"	"	"	"		"	"
	E	15:15-:33			13.6	79	97.08↓	70		7.2(±.3)	113(20)
	SE(N)-UV	15:15-:31	5000 (±700)		"	"	"	"	spitting	"	"
	SE(N)-V	15:21-:33	7330 (±890)		"	"	"	"		"	"
Sept. 25	E(SW)	11:19-34			18.5	93	96.23↓	70	6.6	2.9(±.5)	209(43)
	SW-UV	11:26-36	4810 (±960)		"	"	"	"		"	"
	SW-V	11:24-:36	4220 (±850)		"	"	"	"	thunder-	"	"
	SW-UV	11:20-:32		8070 (±220)	"	"	"	"	storm	"	"
	SW-V	11:35-:48		2070 (±70)	"	"	"	"	overnight	"	"
	E(SE)	13:49-14:09			18.5	84	96.16	"	-fogged	9.4(±.3)	206(20)
	SE(S)-UV	13:54-14:09	3180 (±520)		"	"	"	"	in	"	"
	SE(S)-V	13:51-14:03	6290 (±740)		"	"	"	"		"	"
	SE(S)-V	13:52-14:04		110 (±150)	"	"	"	"		"	"
	SE(S)-UV	14:12-:22		1050 (±40)	"	"	"	"		"	"
Sept. 26	C	14:53-15:06			7.6	33	98.13↑	~200	2.	9.4(±.3)	305(20)
	E	15:36-:52	2260 (13%)		"	"	"	~200		9.3(±.3)	260(21)
	SW-UV	15:42-53	3960 (±740)		"	"	"	"		"	"
	SW-V	15:41-54	3150 (±560)		"	"	"	"		"	"
	SW-UV	15:38-:50		2130 (±70)	"	"	"	"		"	"
	SW-V	16:00-:10		2220 (±70)	"	"	"	"		"	"

* see page 7

TABLE 1 - RADON EMANATION AND METEOROLOGICAL DATA

DATE	* LOCATION	TIME	RADON EXHALATION ($mBq/m^2/s$)		TEMP. (^oC)	RH%	P (kPa)	SOLAR INTENSITY (W/m^2)	RAIN (mm / day)	WIND SPEED (km/h)	WIND DIRECTION ^oE from N.
			AERODYNAMIC	AVG. ACC.							
Sept. 27/84	SE(S)-V	9:56-10:10	4590 (±560)		7.0	82	98.36	355	Nil	5.6(±.2)	210(21)
	E	9:58-10:19			"	"	"	"		"	"
	SE(S)-UV	10:00-:15	5510 (±670)		"	"	"	"		"	"
	SE(S)-V	10:10-:21		500 (±40)	"	"	"	"		"	"
	SE(S)-UV	10:24-:32		1820 (±70)	"	"	"	"		"	"

* see page 7

RADON EXHALATION DATA

Location Symbols:

C	- at meteorological tower
E	- at tailings edge
SW-V, UV	- South West Corner - vegetated/unvegetated patch
SE(S)-V, UV	- South East Corner - south vegetated/unvegetated
SE(N)-V, UV	- South East Corner - north vegetated/unvegetated
UV-1, 2, etc.	- bare patch #1, 2, etc., as illustrated on Figure 1
R	- remote location, i.e. away from tailings

See map locations (Figure 1):

UV-1	- unvegetated area in SE area near peizometer #T7P5
UV-2	- unvegetated patch near intersection of perimeter and north-south road
V-2	- vegetated patch near UV-2
UV-3	- semi-vegetated area 0.5 km west of meteorological tower
UV-4	- semi-vegetated area ~400 m west of dead tree
UV-5	- unvegetated patch in south east corner of tailings
UV-6	- unvegetated patch near wier
UV-7	- bare patch beside wells #T3P5, ~1 km S55^{O}E of met. tower, alongside centre road
UV-8	- bare patch ~13 m W5^{O}N of well #T7P5
UV-9	- bare patch NE quadrant, 70 m north of centre road, 100 m west of dam (sparcely vegetated - mosses)

TABLE 2

TERRADEX RESULTS

Exposure Time	Location *	Depth (m)	Radon (mBq/m^3)	Gradient ($mBq/m^3/m$)
Aug. 16-21/84	SE-V	15	199.2	-14.0×10^3
	"	40	3708.5	
"	SE(S)-UV	15	1965.5	-6.7×10^3
	"	40	3649.1	
"	SW-V	15	749.1	-1.5×10^3
	"	30	971.6	
"	SW-UV	15	823.3	-7.9×10^3
	"	40	2006.3	
Sept. 24-28/84	SE-V	10	305.9	-2.4×10^3
"	"	10	281.8	
"	"	40	834.4	
"	"	40	1214.5	
"	SE-UV	10	88.5	-2.3×10^3
"	"	10	105.4	
"	"	40	832.1	
"	"	40	737.0	

* See PAGE 7 of TABLE 1 for explanation of symbols.

TABLE 3

RADON EMANATION POWER (DRY) OF TAILINGS SAMPLES

Date	Time	Location *	Emanation Power (mBq/g)
May 30/84	13:35	C	636 (±30)
"	14:15	UV-2	360 (±19)
June 21	22:00	C	662 (±30)
"	15:40	SW-UV	422 (±30)
June 22	11:40	UV-1	474 (±20)
June 23	10:40	UV-2	418 (±30)
June 24	12:00	UV-3	762 (±41)
June 25	13:40	UV-4	559 (±30)
June 26	9:00	UV-5	359 (±15)
July 20	16:40	SW-V	2540 (±81)
"	16:40	SW-UV	240 (±10)
Aug. 21	12:30	SE-UV	762 (±41)
"	"	"	810 (±30)
"	13:15	SE(S)-V	448 (±30)
"	"	"	759 (±41)
"	13:45	SW-UV	414 (±19)
"	"	"	603 (±33)
"	14:30	SW-V	920 (±41)
"	"	"	1340 (±70)

* See explanation of location symbols on Page 7 of Table 1.

TABLE 4

TENSIOMETRIC AND SOIL MOISTURE DATE

DATE / TIME	LOCATION *	TENSIOMETER READINGS (kPa)					GRAVIMETRIC	
		0 m	0.1 m	0.2 m	0.3 m	0.4 m	Depth (m)	Moisture (% Mass)
May 30/84 13:35	C						.05-.13	31.50
May 30 14:15	UV-2						.03-.10	7.55
June 21 14:40	C				18			
22:00	C				12		0-.15	7.45
15:40	SW-UV				12		0-.15	9.57
June 22 10:39	C			8		8		
11:40	UV-1			18		18	0-.15	1.99
June 23 9:40	C			13		14		
10:40	UV-2			21		19	0-.15	7.48
June 24 10:50	C			18		15		
12:00	UV-3			12		11	0-.15	3.09
June 25 13:40	UV-4			14		14	0-.15	10.87
June 26 8:30	C			16		16		
9:00	UV-5			13		13	0-.15	7.80
July 17 18:00	SW-V	6	8	10	11	14		
18:00	SW-UV	7	7	9.5	12	12		
July 20 16:40	SW-V	13	16	15	14	14	.05-.10	37.78
16:40	SW-UV	29	19	16	16.5	15	.10-.12	7.39
July 22 16:30	SE(S)-V	30	29	25	20	21		
16:30	SE-UV	20	16	18.5	19	17		
Aug. 14 12:00	V-2	-	8.5	14	15	-	.10	17.75

TABLE 4

TENSIOMETRIC AND SOIL MOISTURE DATE

DATE / TIME	LOCATION *	TENSIOMETER READINGS (kPa)					GRAVIMETRIC	
		0 m	0.1 m	0.2 m	0.3 m	0.4 m	Depth (m)	Moisture (% Mass)
Aug. 14/84 12:00	UV-2	10	9.5	11.5	13	14.5	.10-.15	6.75
Aug. 15 16:00	SW-V	10.0	10	9	hit a void	10	.08-.10	23.30
16:00	SW-UV	10.5	9.5	11.0	11.0	12.5	.10-.12	21.38
Aug. 16 pm	SE-UV			9		8		
pm	SE(S)-V			10		15		
pm	SW-V			11		11		
pm	SW-V			9	9.5		.30-.40	31.46
Aug. 18 16:40	C		8	8		8		
17:50	UV-6	10	9.5	10	-	10		
Aug. 19 11:40	C		11		18	22		
12:20	UV-7		25	26				
12:20	V-7		19	20				
13:50	UV-8		9		8			
13:50	V-8		10		10			
20:30	SE(S)-V			9		11		
20:30	SE-UV			7.5	7			
20:30	SW-V			9	8			
20:30	SW-UV			8		8		
Aug. 20 11:00	C		9		13			
12:30	SW-UV			12		10.5		
12:30	SW-UV		12	12	12	11.5		
13:30	SW-V			11	9			
13:30	SW-V		11	11		10.5		
Aug. 21 12:30	SE-UV			11		9	. 15 . 40	13.69 21.50

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TABLE 4

TENSIOMETRIC AND SOIL MOISTURE DATE

DATE / TIME	LOCATION *	TENSIOMETER READINGS (kPa)					GRAVIMETRIC	
		0 m	0.1 m	0.2 m	0.3 m	0.4 m	Depth (m.)	Moisture (% Mass)
Aug. 21/84								
13:15	SE(S)-V			14		13	.15	7.71
							.40	13.69
13:45	SW-UV			14.5		12.5	.15	6.90
							.40	14.10
14:30	SW-V			12.5	11		.15	9.87
							.30	32.27
Aug. 22								
12:00	UV-9		11.5	11	10			
12:00	V-9		10.5	10	9			
Sept. 24								
9:40	SE-UV	10	9	9				
9:40	SE(S)-V	18	18	18	16	14		
15:30	SE-UV	10	12	10				
15:30	SE(S)-V		10			15		
Sept. 25								
11:40	SW-V	8	9.3	9				
11:40	SW-UV	8	13	11	11.5			
13:30	SE(S)-V	8.5	9.5	10.5				
14:20	SE-UV	7	8	8	10			

* See explanation of symbols on page 7 of Table 1.

TABLE 5

TAILING SAMPLE LOCATIONS

SAMPLING POSITIONS (N.B. Depths to Top of Cores)	LEVEL 1		LEVEL 2	
	Depth (m)	Core Identification Numbers	Depth (m)	Core Identification Numbers
South West Corner - Vegetated	0.10	35, 11	0.40	58, 11
South West Corner - Unvegetated	0.10	14, 17	0.40	107, 12
South East Corner - Vegetated North Patch	0.05	39, 0	0.30	45, 19
South East Corner - Vegetated North Patch (near dam)	0.03	50, 18	0.30	32, 8
South East Corner - Unvegetated White cohesive	0.03	85, 15	0.30	71, 16
South East Corner - Unvegetated Sandy	0.03	79, 14	0.30	102, 7

TABLE 6

TAILING BULK DENSITY RESULTS

Depth	AVERAGE BULK DENSITY OF TAILING CORES (kg/m^3)	
	Unvegetated	Vegetated
0.03 to 0.10 m (surface)	1.46×10^3	1.32×10^3
0.10 to 0.30 m (subsurface)	1.50×10^3	1.42×10^3

Overall average = 1.42×10^3 kg/m^3

TABLE 7

TAILING HYDRAULIC CONDUCTIVITY RESULTS

Depth	AVERAGE HYDRAULIC CONDUCTIVITY OF TAILING CORES (m/s)	
	Unvegetated	Vegetated
.03 to .10 m (surface)	3.74×10^{-5} (rapid)*	$.90 \times 10^{-5}$ (moderate)*
.10 to .30 m (subsurface)	1.01×10^{-5} (moderate)*	0.67×10^{-5} (moderate)*

Geometric mean = 1.20×10^{-5} m/s

* Conductivity classes based on O'Neal (1952).

TABLE 8

SOIL WATER DESORPTION CHARACTERISTIC VALUES

Matric Pressure kPa (pF)*	VOLUMETRIC WATER CONTENT (m^3water/m^3bulk) 0 -	-5 1.7	-10 2.0	-33 2.5	-1500 4.2	*** Available Water (m^3/m^3)
Core Number	Unvegetated, Surface					
14	.548	.441	.373	.293	.230	.143
85	.515	.402	.202	.088	.039	.163
79	.481	.338	.200	.074	.042	.158
	Unvegetated, Subsurface					
107	.459	.271	.220	.171	.111	.109
71	.460	.293	.186	.148	.064	.122
102	.504	.370	.237	.173	.076	.161
	Vegetated, Surface					
39	.545	.381	.281	.189	.097	.184
35	.565	.440	.320	.286	.206	.114
50**	.660	.500	.467	.415	.314	.153
	Vegetated, Subsurface					
45	.520	.391	.279	.226	.189	.090
58	.511	.391	.298	.177	.058	.240
32	.481	.410	.395	.334	.246	.150
						AVG.=.149

* pF = $-\log_{10}$ (-matric pressure in cm water head)

** Core #50 - Very noticeable high content of root and fibrous material

*** Available water is the difference in volumetric water content at -1500 kPa compared to that at -10 kPa.

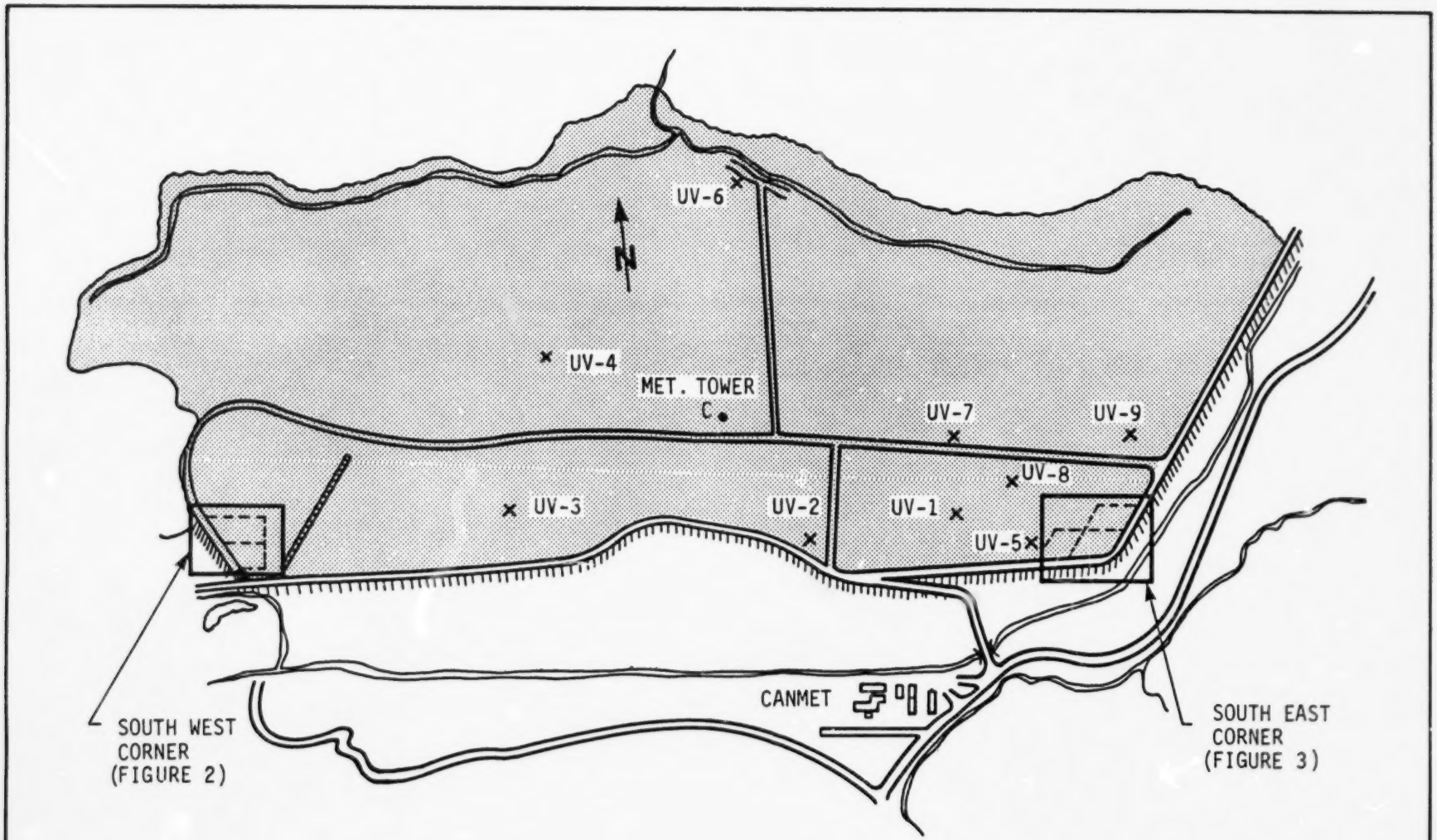

FIGURE 1 NORDIC TAILINGS SITE

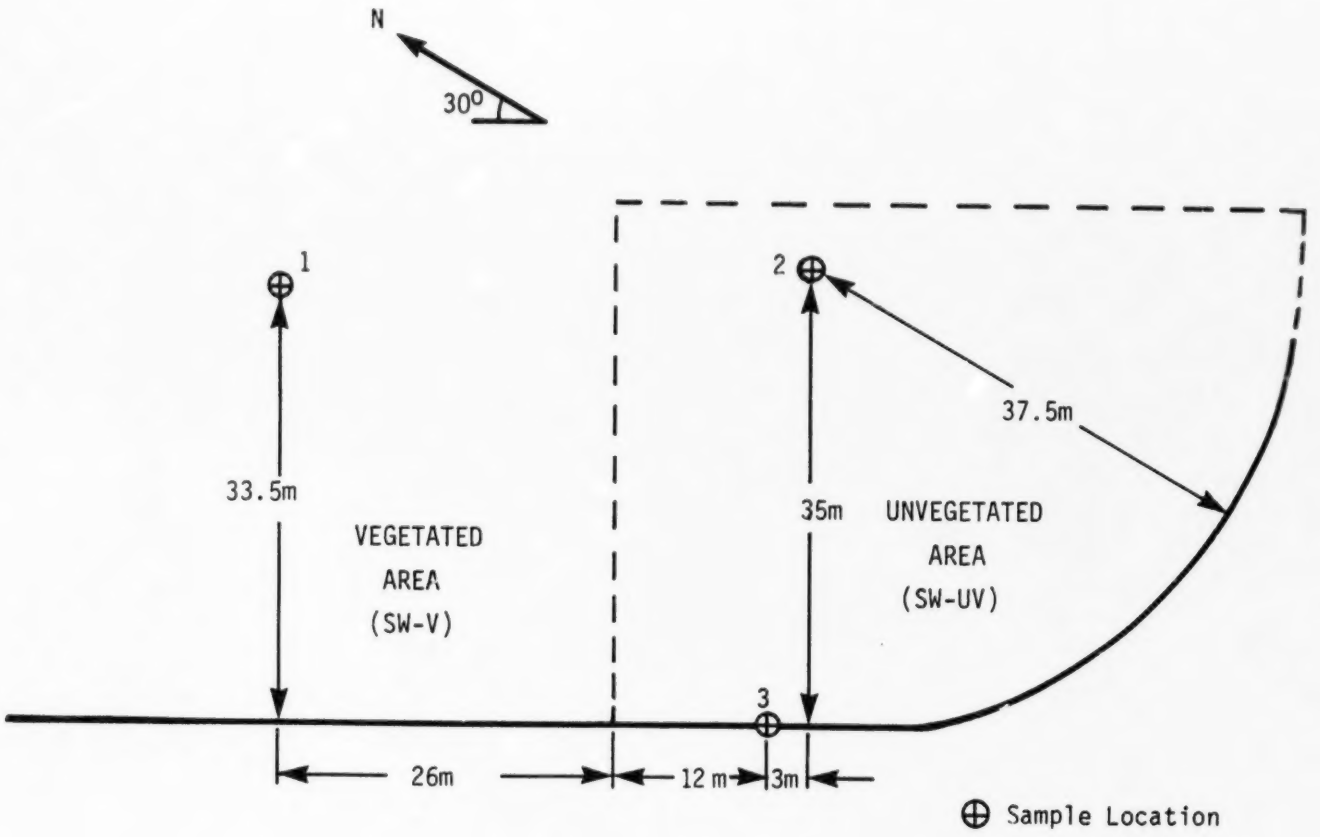

FIGURE 2 AERODYNAMIC SAMPLE LOCATIONS IN SOUTH WEST CORNER OF NORDIC TAILINGS SITE

DSMA ATCON LTD.

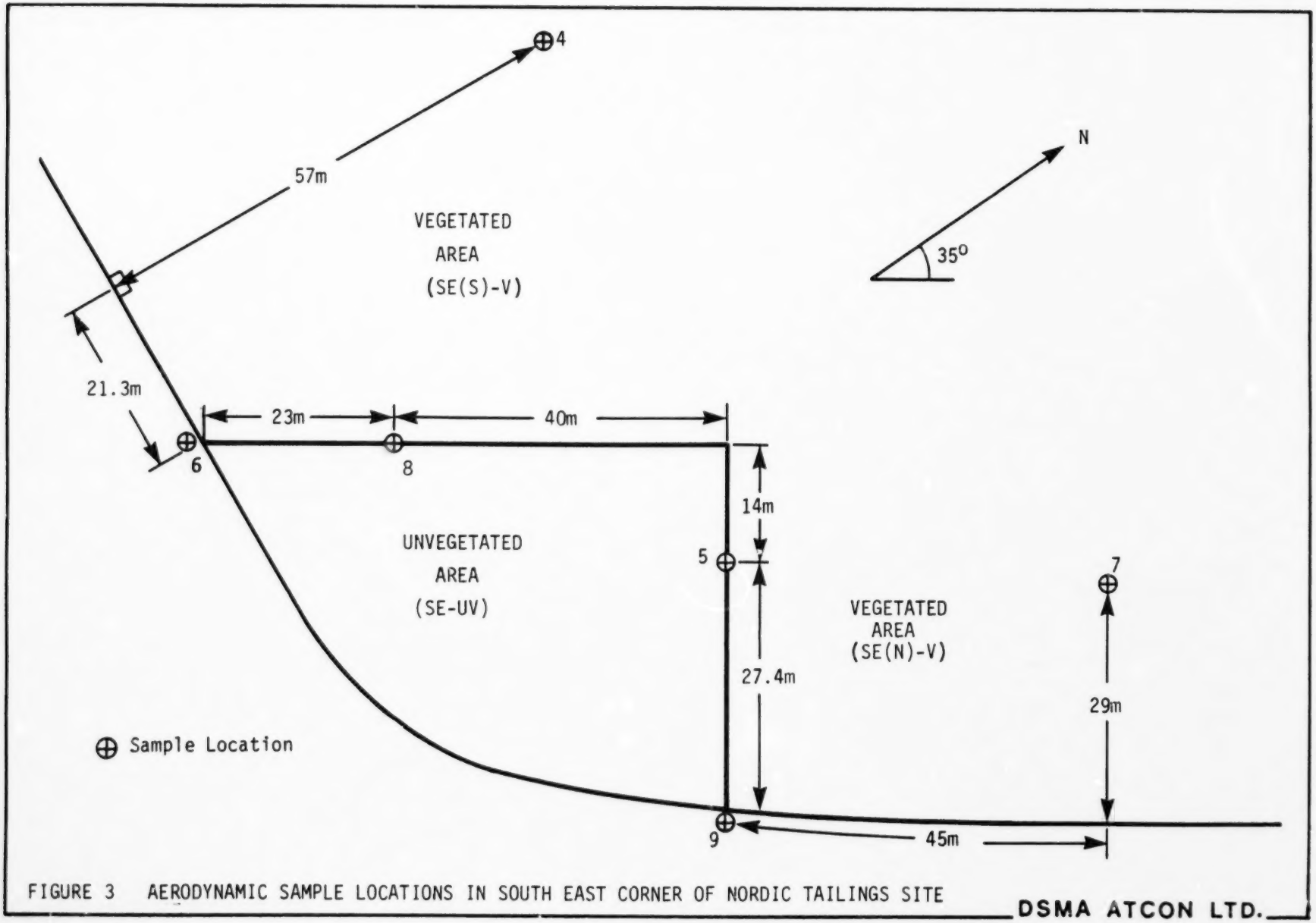

FIGURE 3 AERODYNAMIC SAMPLE LOCATIONS IN SOUTH EAST CORNER OF NORDIC TAILINGS SITE

DSMA ATCON LTD.

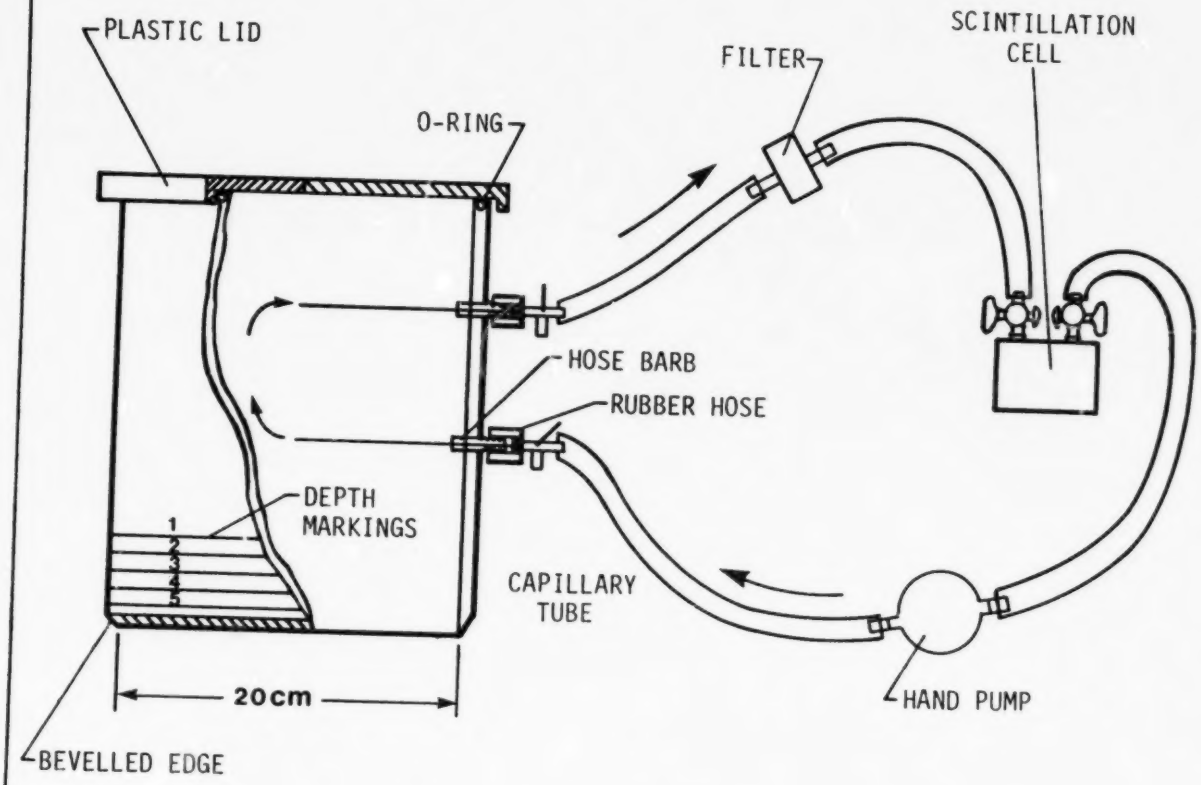

FIGURE 4 - DIAGRAM OF SMALL RADON ACCUMULATOR

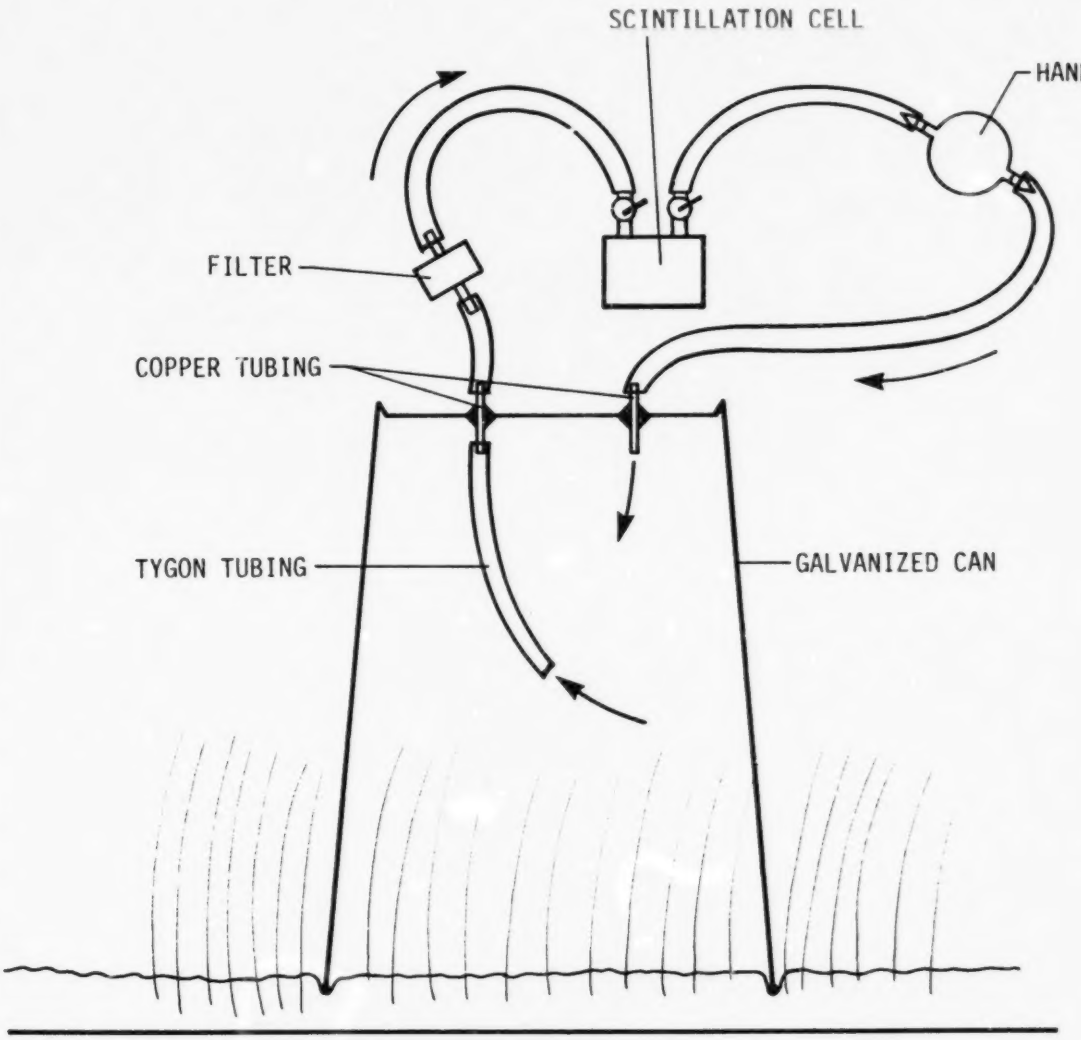

FIGURE 5 - DIAGRAM OF LARGE ACCUMULATOR

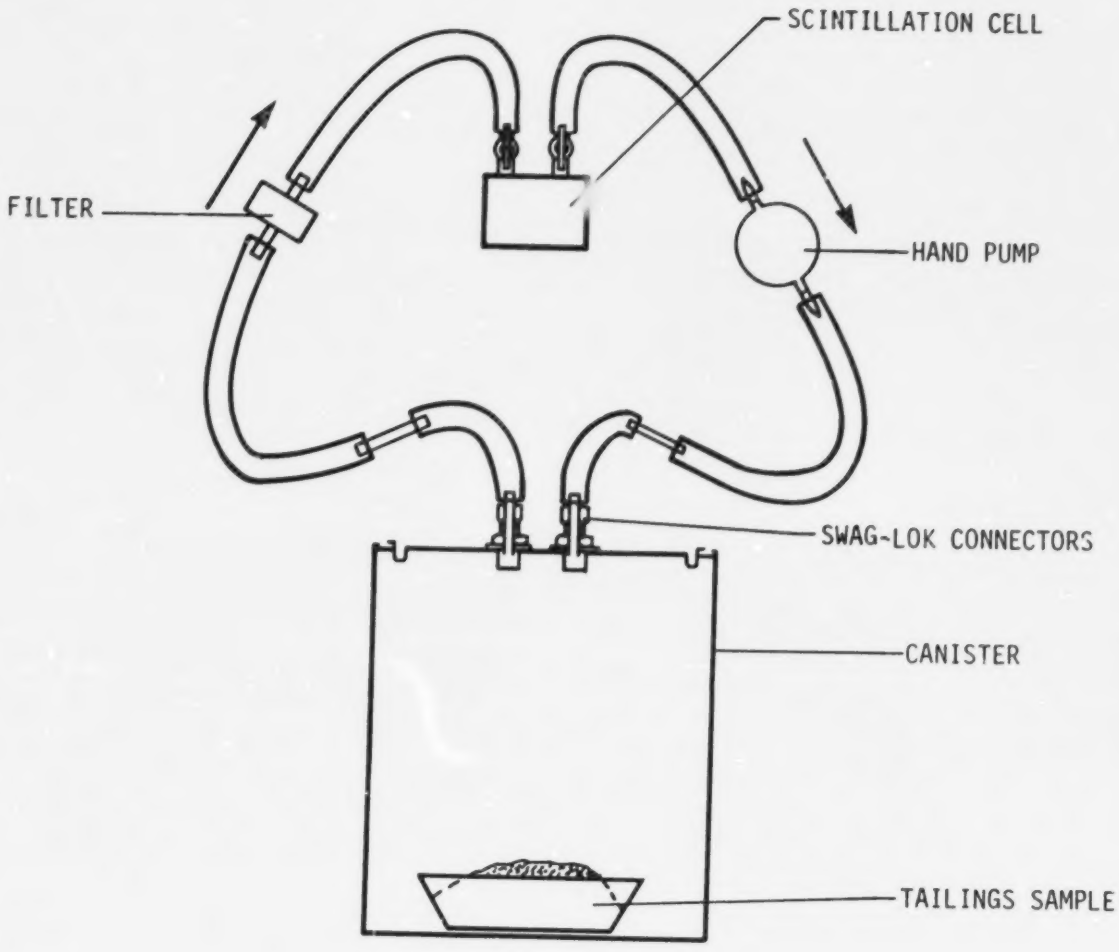

FIGURE 6 - EMANATION POWER OF TAILINGS SAMPLES

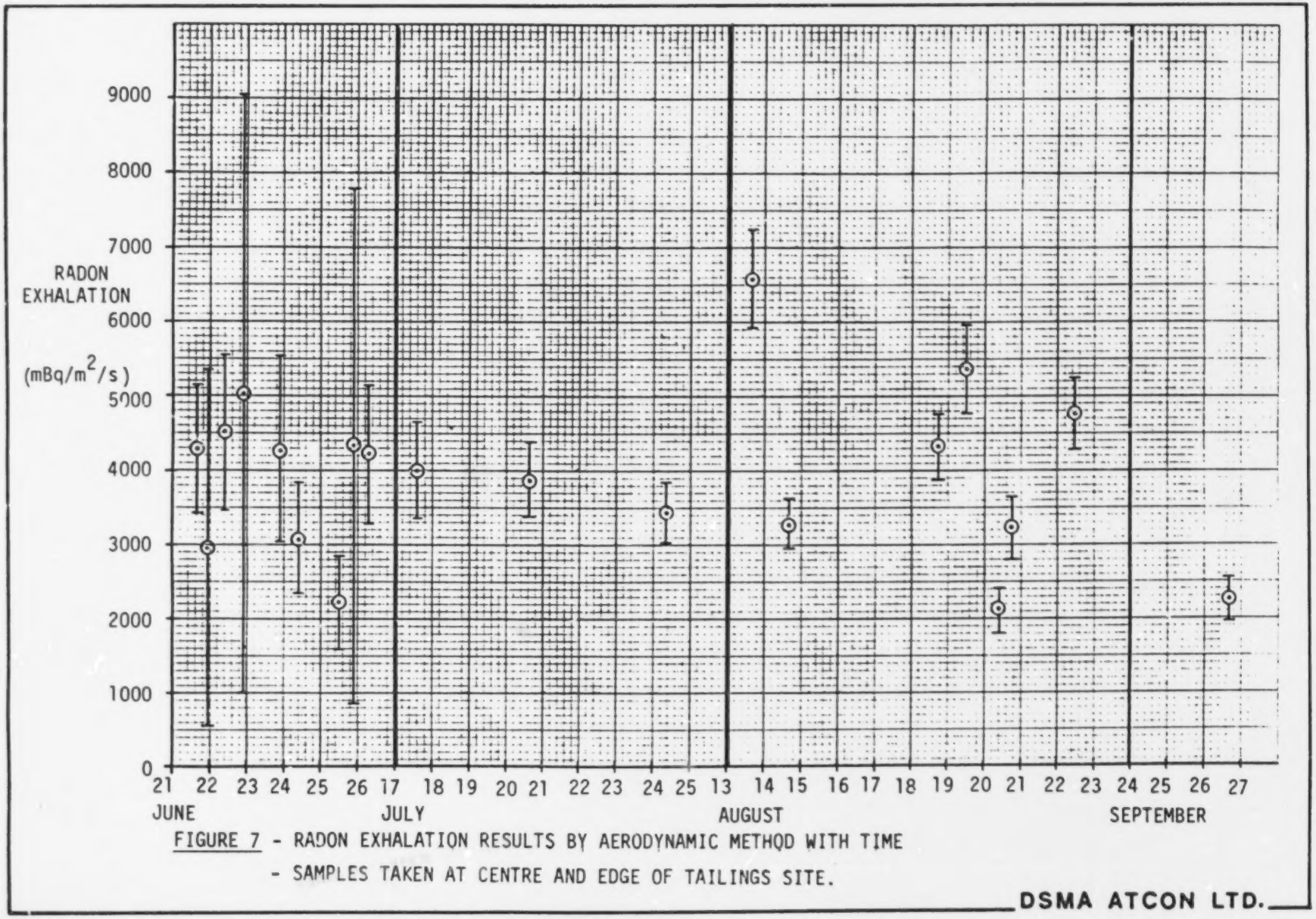

FIGURE 7 - RADON EXHALATION RESULTS BY AERODYNAMIC METHOD WITH TIME
- SAMPLES TAKEN AT CENTRE AND EDGE OF TAILINGS SITE.

DSMA ATCON LTD.

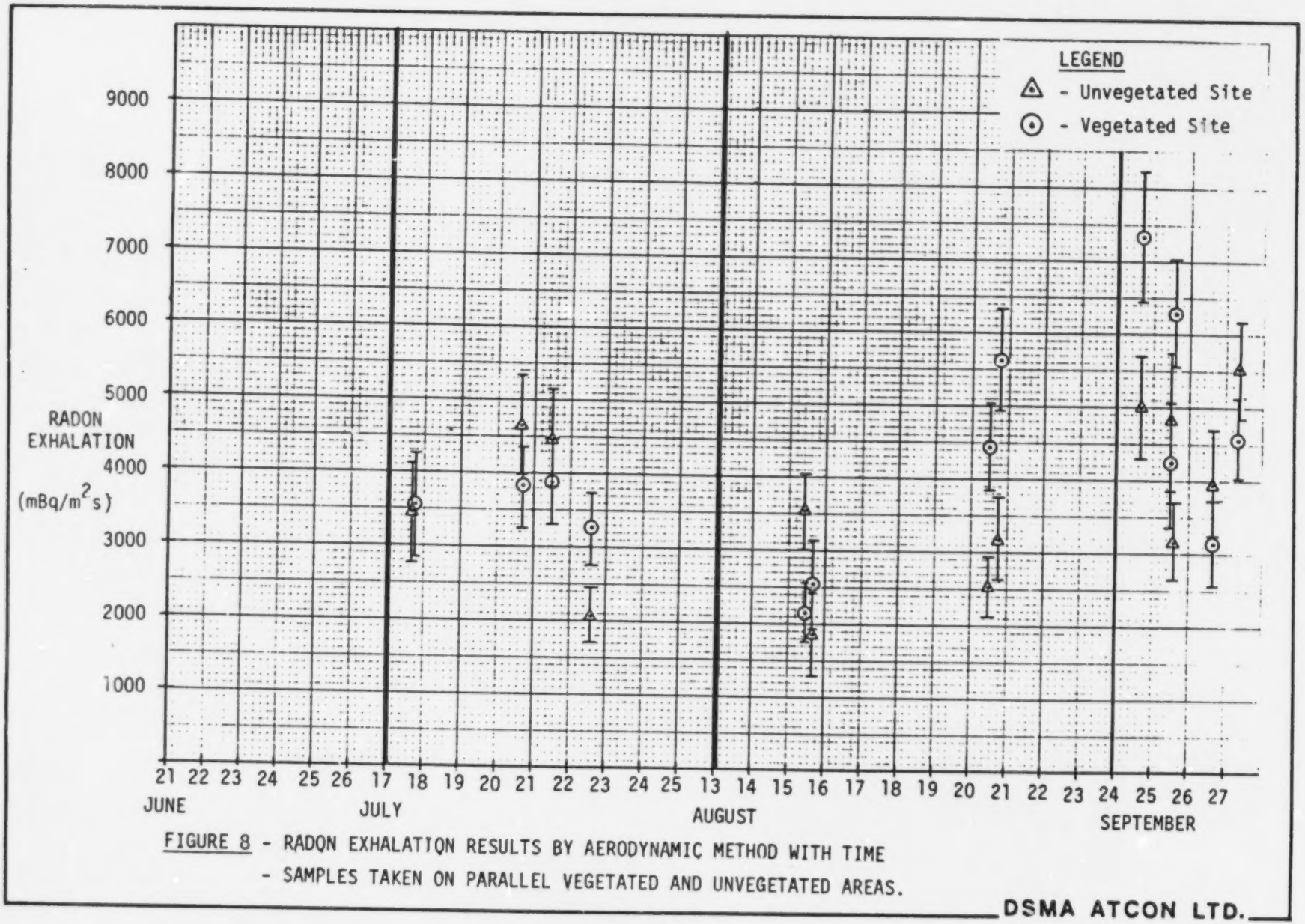

FIGURE 8 - RADON EXHALATION RESULTS BY AERODYNAMIC METHOD WITH TIME
- SAMPLES TAKEN ON PARALLEL VEGETATED AND UNVEGETATED AREAS.

DSMA ATCON LTD.

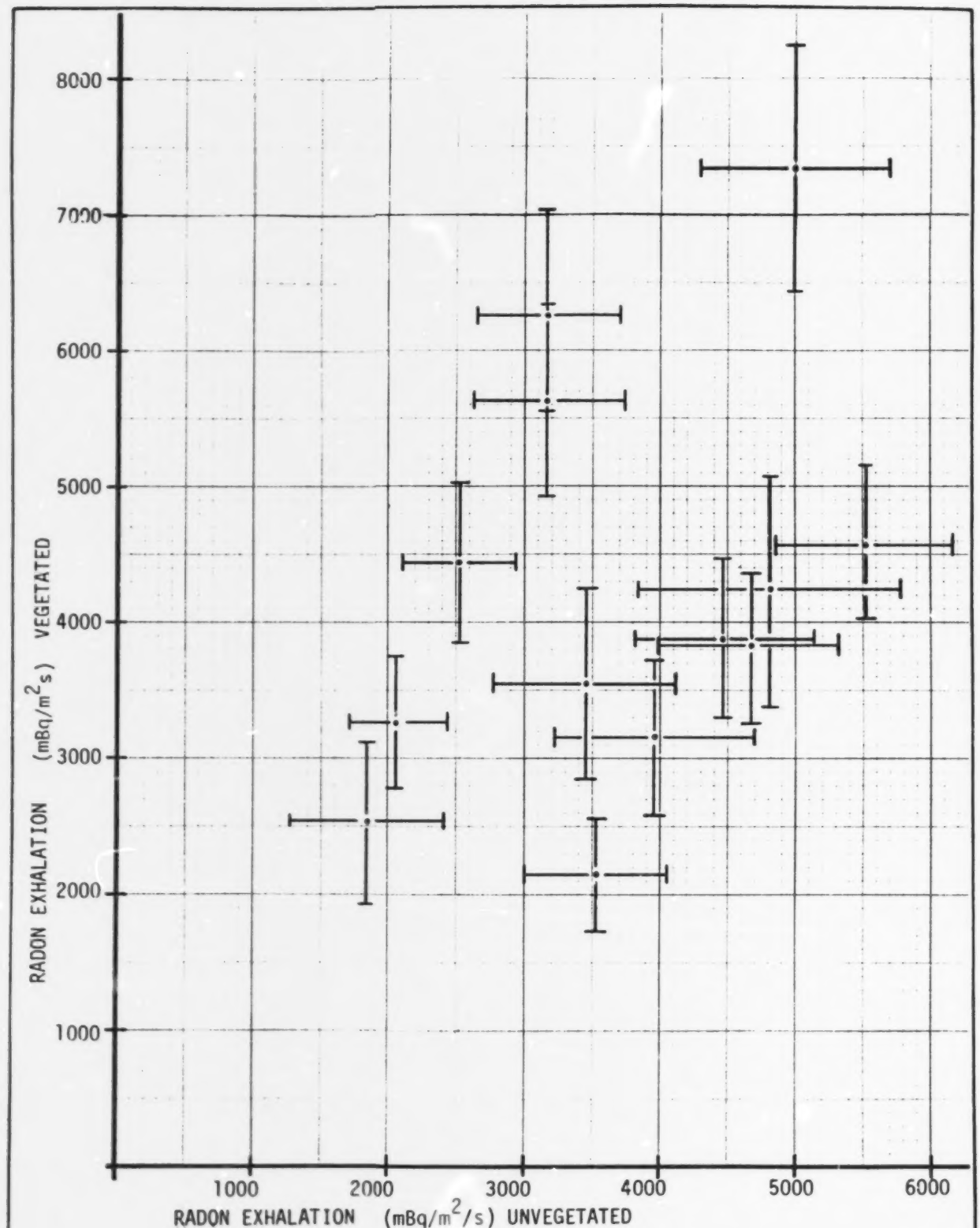

FIGURE 9 - RADON EXHALATION RESULTS BY AERODYNAMIC METHOD
- SIMULTANEOUS VEGETATED VERSUS UNVEGETATED RESULTS ON PARALLEL AREAS.

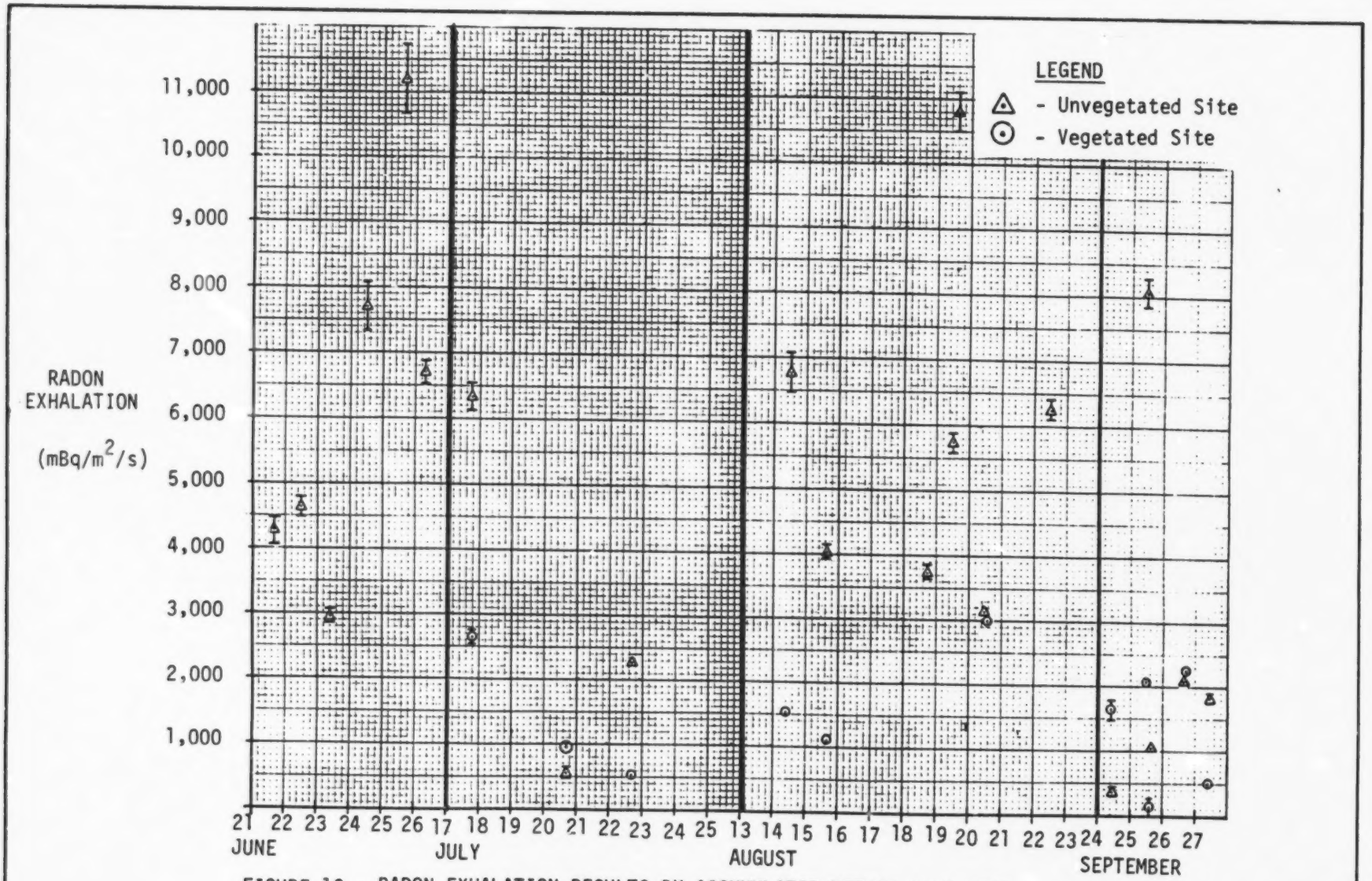

FIGURE 10 - RADON EXHALATION RESULTS BY ACCUMULATOR METHOD WITH TIME - AVERAGE UNVEGETATED AND VEGETATED.

DSMA ATCON LTD.

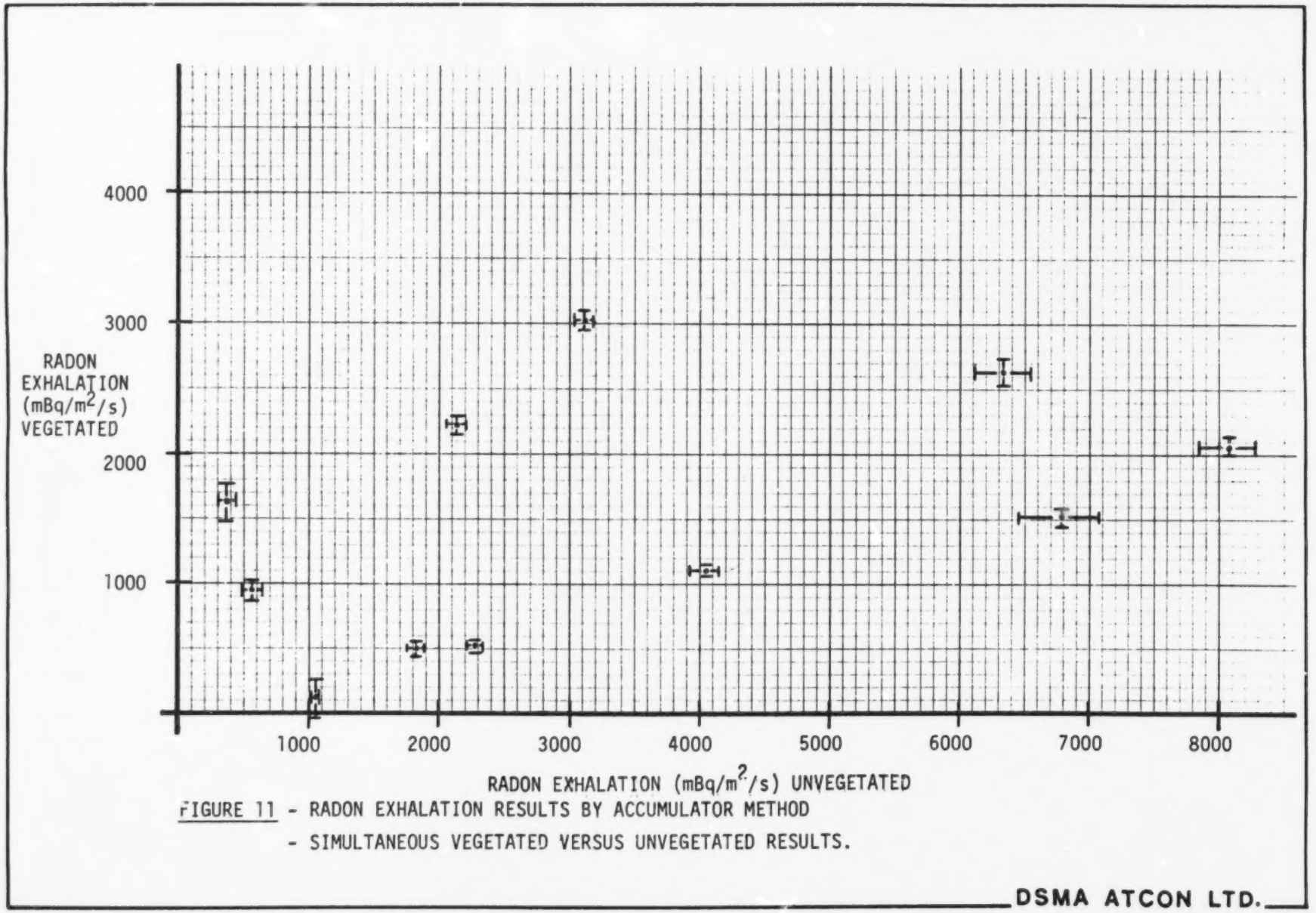

FIGURE 11 - RADON EXHALATION RESULTS BY ACCUMULATOR METHOD
- SIMULTANEOUS VEGETATED VERSUS UNVEGETATED RESULTS.

DSMA ATCON LTD.

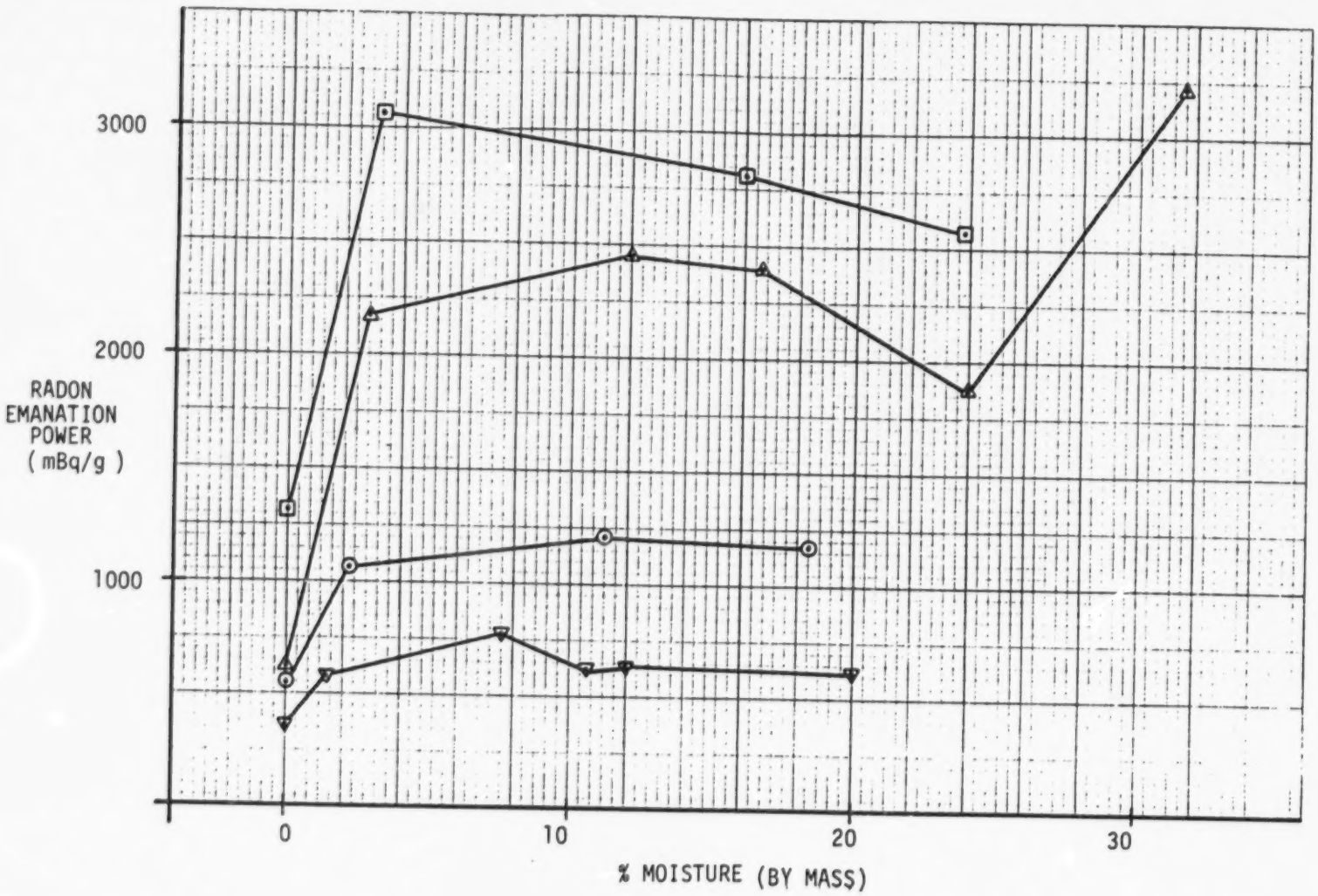

FIGURE 12 - TAILINGS RADON EMANATION POWER VERSUS MOISTURE CONTENT.

DSMA ATCON LTD.

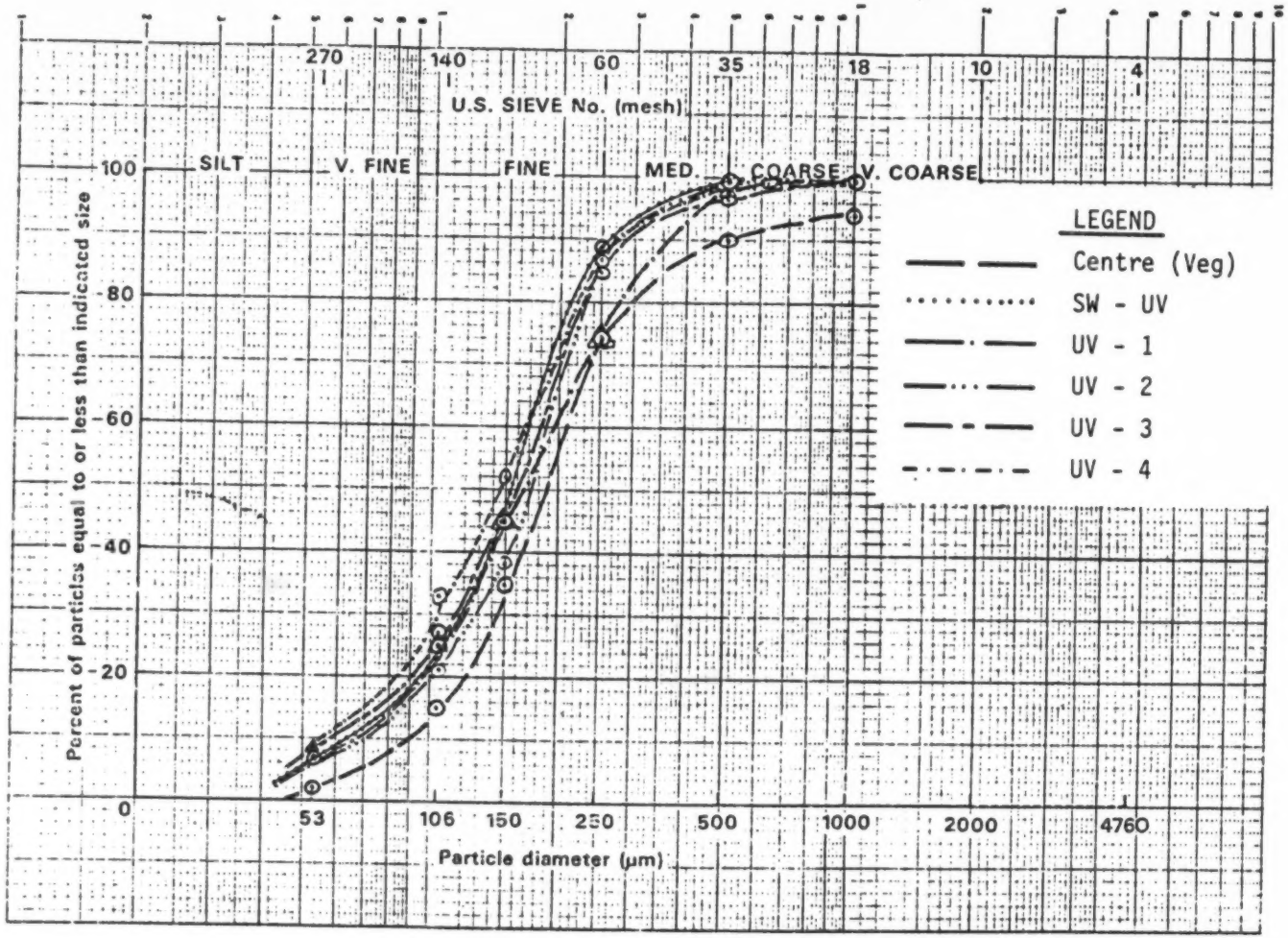

FIGURE 13 - PARTICLE SIZE ANALYSIS OF URANIUM TAILINGS (DEPTH 0-15cm)

DSMA ATCON LTD.

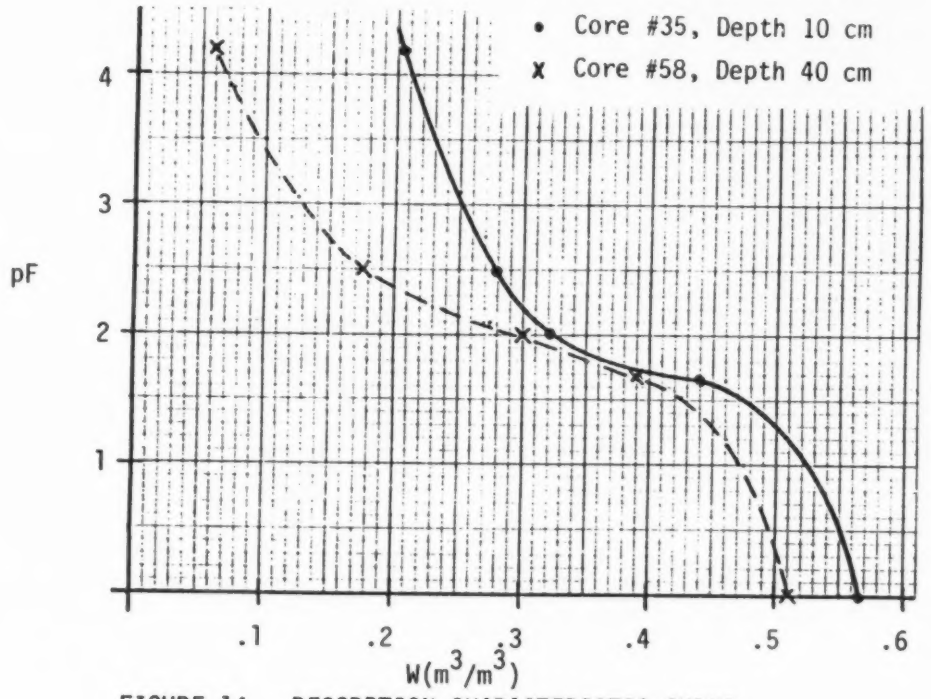

FIGURE 14 - DESORPTION CHARACTERISTIC CURVE
- SOUTH WEST CORNER VEGETATED

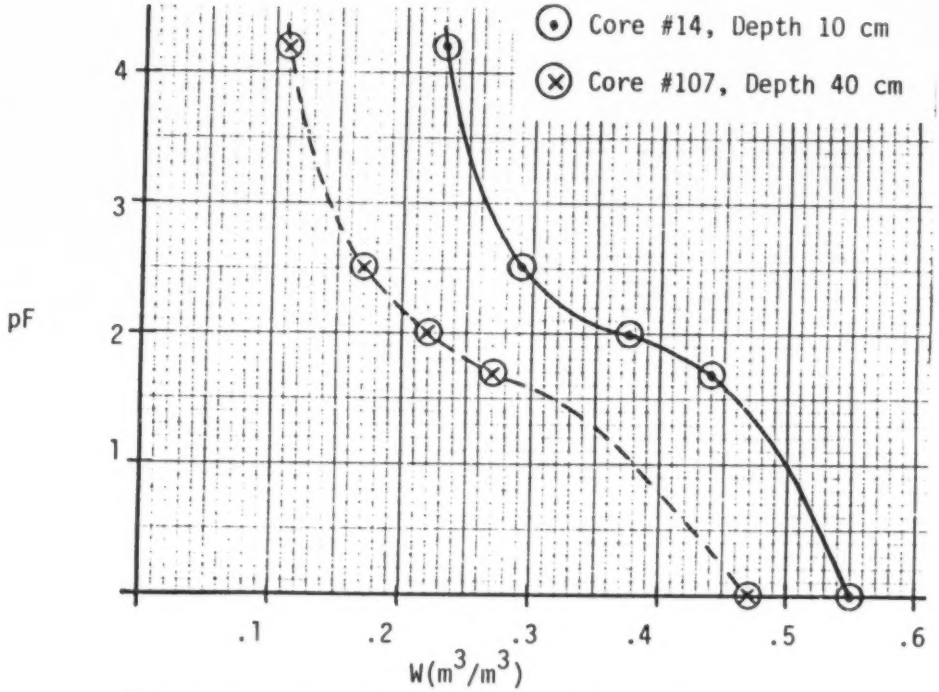

FIGURE 15 - DESORPTION CHARACTERISTIC CURVE
- SOUTH WEST CORNER UNVEGETATED.

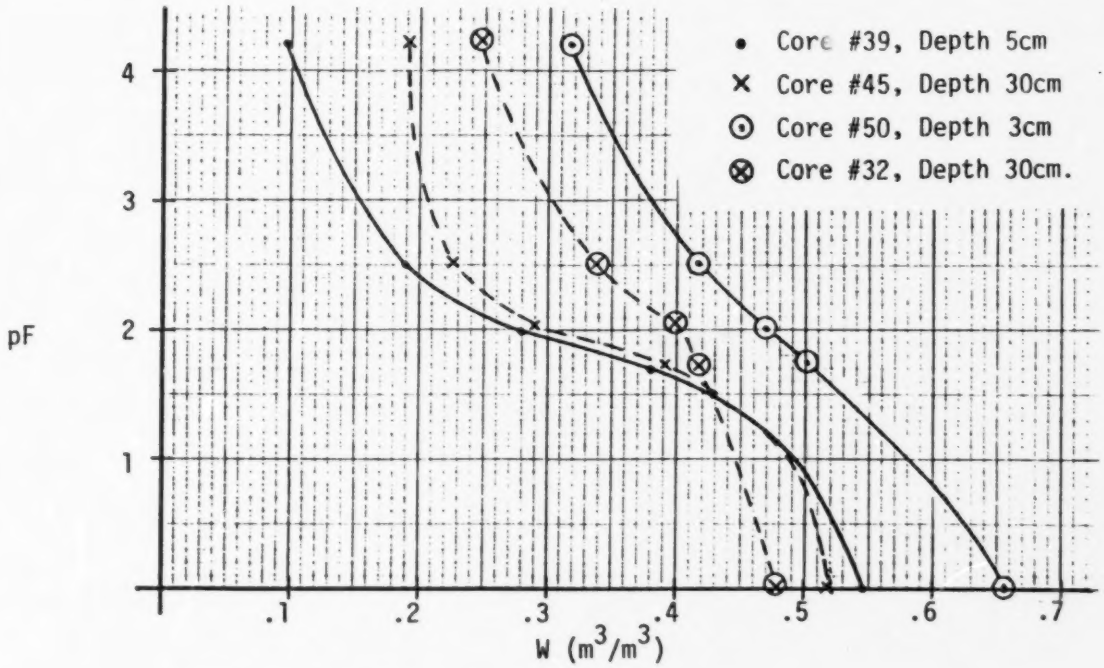

FIGURE 16 - DESORPTION CHARACTERISTIC CURVE
- SOUTH EAST CORNER VEGETATED.

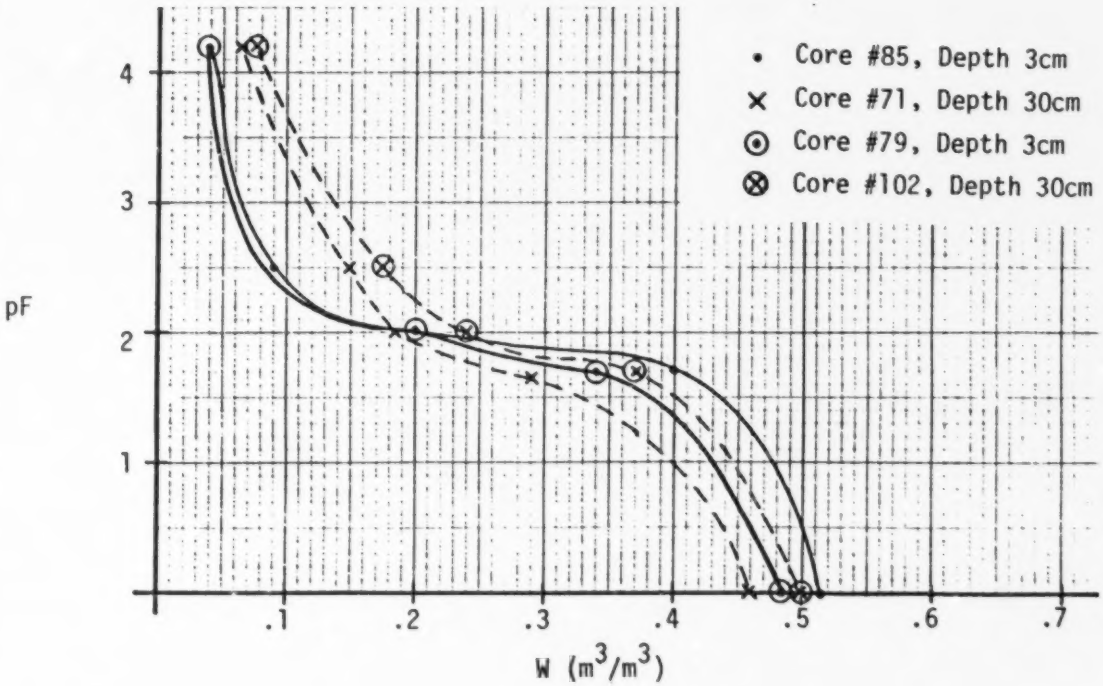

FIGURE 17- DESORPTION CHARACTERISTIC CURVE
- SOUTH EAST CORNER UNVEGETATED.